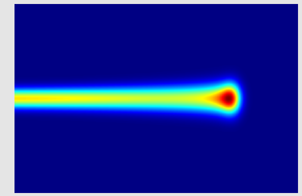

David Meer :: Center for Proton Therapy :: Paul Scherrer Institut

# Progress in Particle Therapy Enabled by Technology

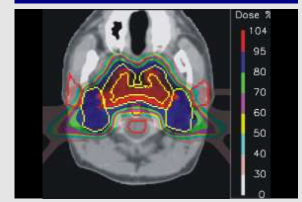
21st IEEE Real Time Conference - Colonial Williamsburg, June 15th 2018

# Contents and goal

1. From conventional delivery technique to pencil beam scanning

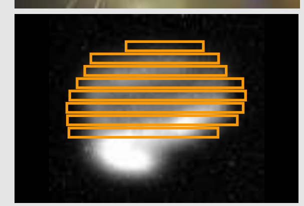


2. Advantages of pencil beam scanning




3. Fast scanning possibilities with PSI Gantry 2

4. Organ motion and mitigation techniques



5. Implementation of highly dynamic beam delivery

# Bragg peak of charged particles

- Charged particles have defined range in  matter depending initial on energy
- Maximum energy loss before particle come to rest → Bragg peak
- Clinical use already suggested by Robert R. Wilson in 1946:

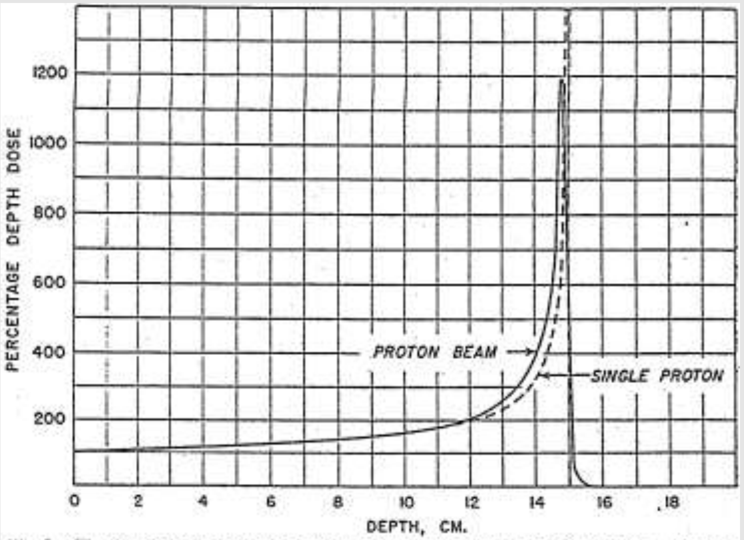
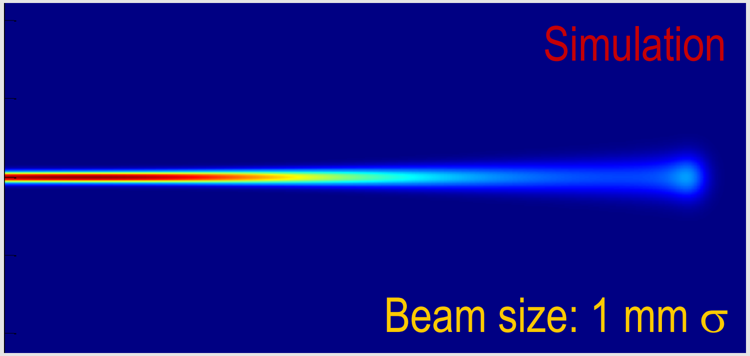
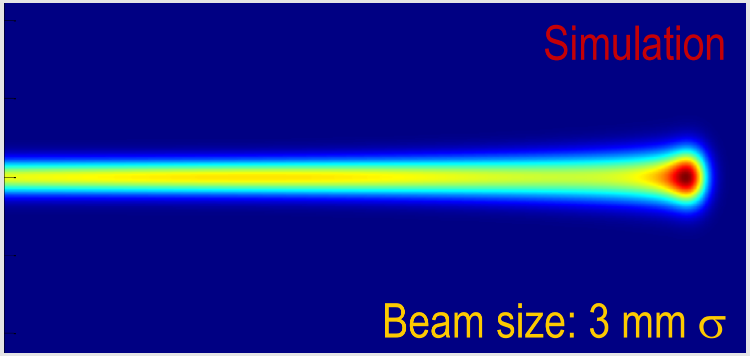
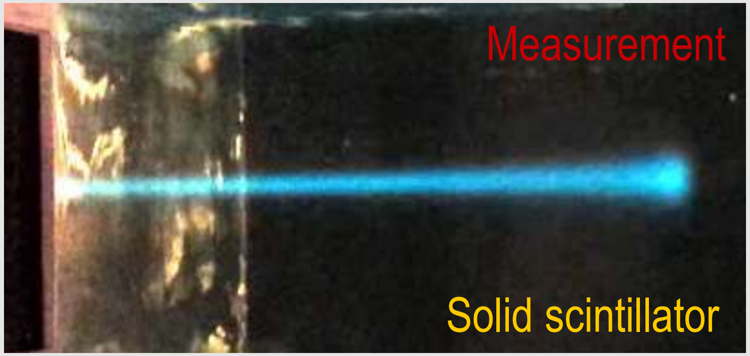



Fig. 2. The dotted curve shows the relative dose due to a single 140 Mev proton. The full curve shows qualitatively the depth dose curve for a beam of 140 Mev protons in tissue.

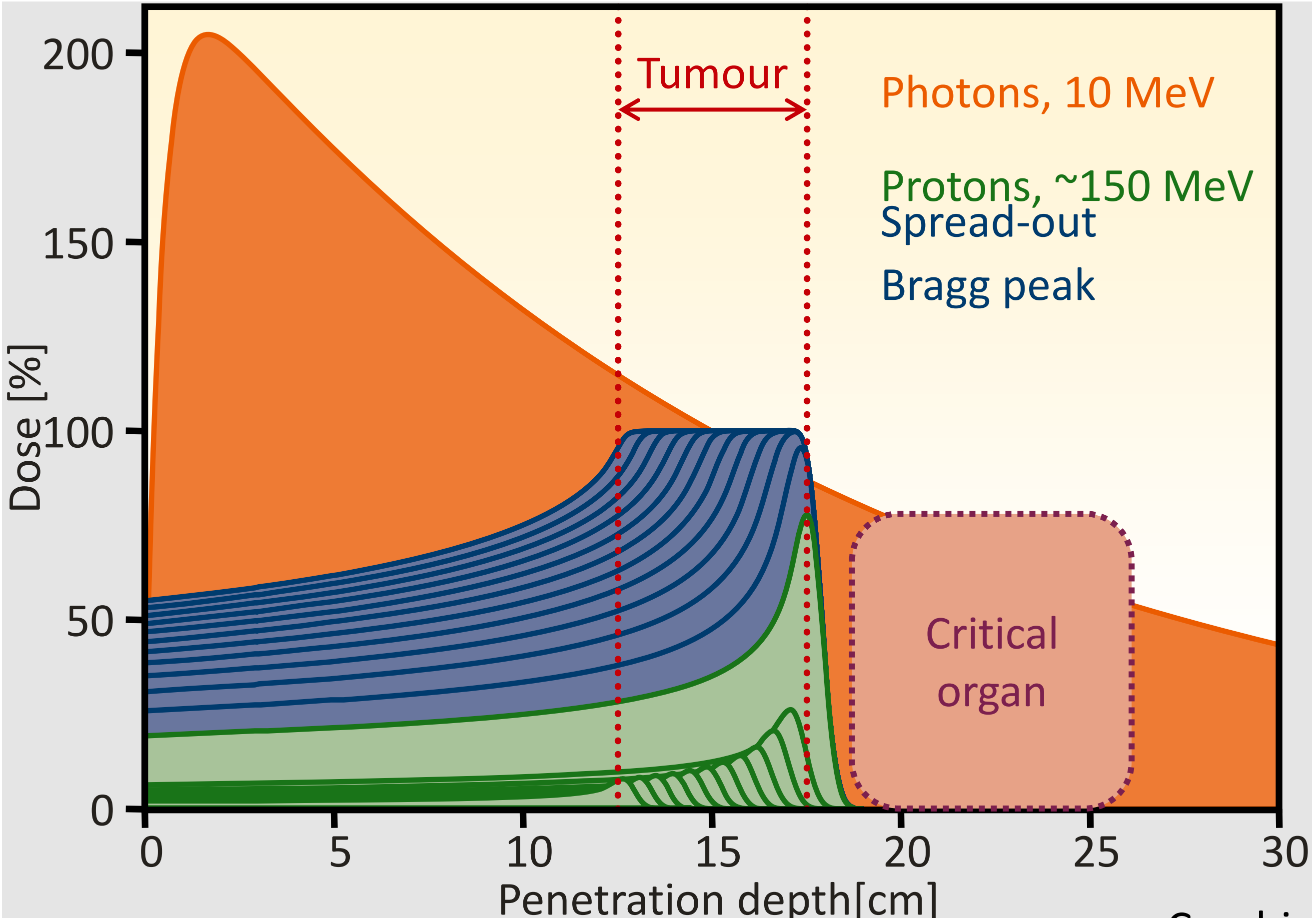
Wilson, *Radiological Use of Fast Protons*, Radiology, **47**:487-491 (1946)

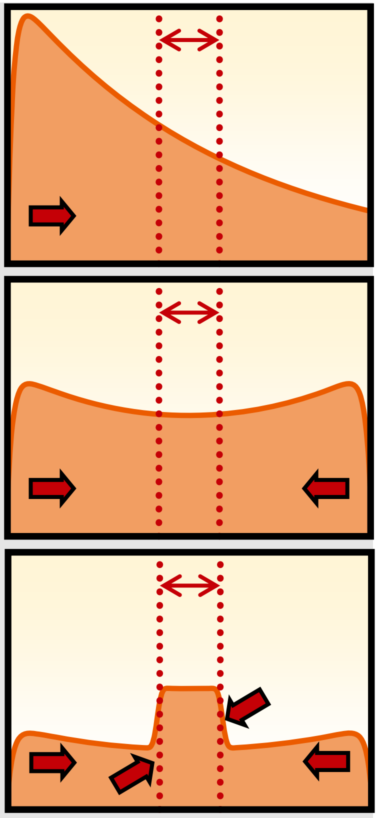


# Irradiation of a deep seated tumour with conventional (photon) and proton therapy



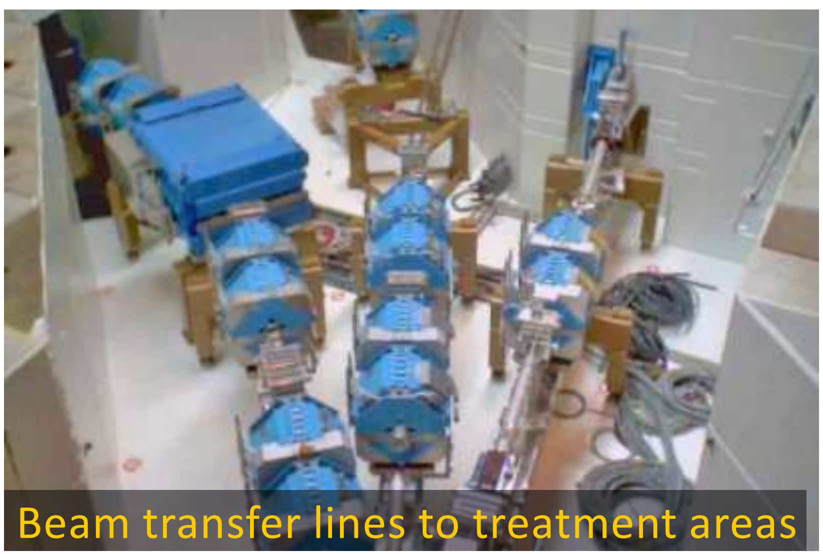
- ➢Better dose conformation to target / tumour
- ➢Less dose to healthy tissue

Combination of different field directions
→ use of gantries

# Main parts of a particle treatment facility


Accelerator – charged particles source

Fixed beam line

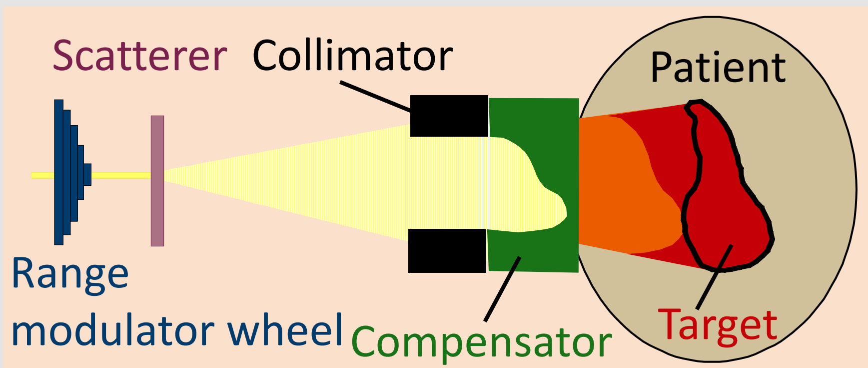


Beam transfer lines to treatment areas

Gantry – rotating beam line

# Original beam shaping to the target with mechanical devices (passive scattering)

- Proton treatments started with passive dose shaping (1960's, Harvard cyclotron)




**Rotating wheel**

- Fast (~ 100ms/cycle) SOBP creation

**Collimator** (field specific)

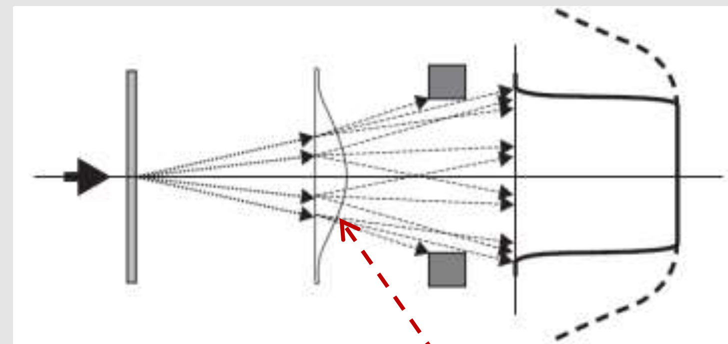
- Lateral conformation to target

**Compensator** (field specific)

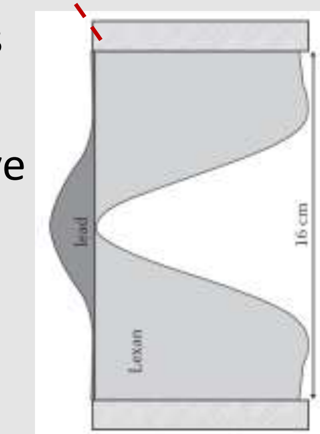
- Conform distal fall-off to target

**Double contoured 2nd scatterer**

- Increase efficiency by 2nd scatterer that flattens center of field



- Extra low-Z material to compensate energy loss at edges
- Today predominant technique for passive scattering



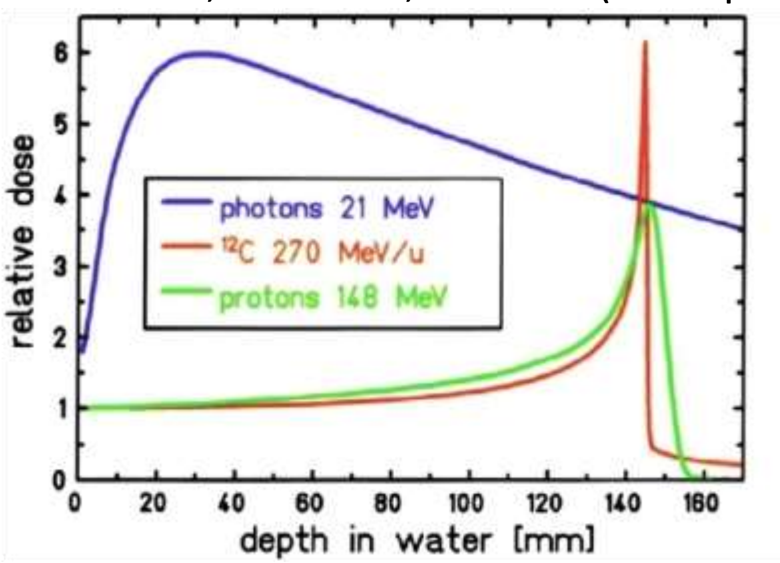

Simple concept but complex practical realisation

# Example of scattering beam line at PSI: OPTIS2 - treatment of eye tumours (1984-)

- Treatment of uveal melanomas
- Double scattering system
- Treatment of ~250 patients/year; 6500 patients in total
- 5 year local tumour control rate: >98%
- 25% of all eye irradiations worldwide were performed at PSI
- Vision can be preserved in many cases

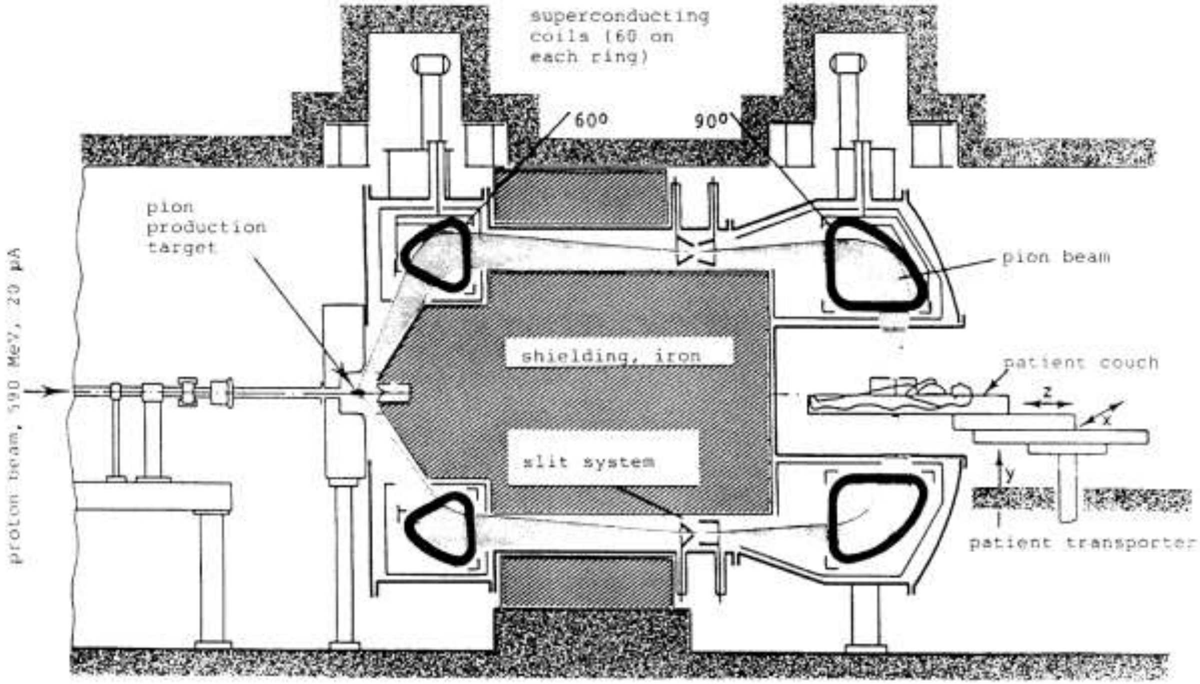
# Other charged particles?

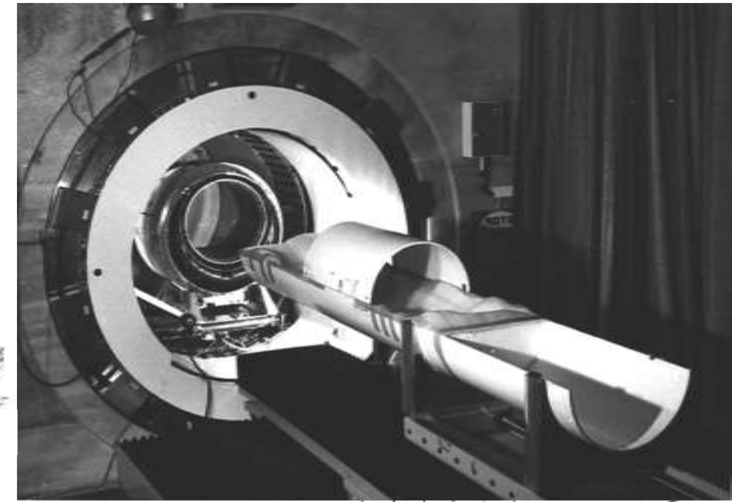
- Protons, carbon and helium ions; pions
  - Bragg Peak, fragmentation
  - High ↔ Low LET (Linear Energy Transfer)
  - RBE > 1 (Radio-Biological Effectiveness)
  - Magnetic rigidity of beam
    3x larger for carbon than protons
- Patients treated with: p: 150’000,
  C: 22’000, He: 2000, $\pi^-$: 1000 (www.ptcog.ch)



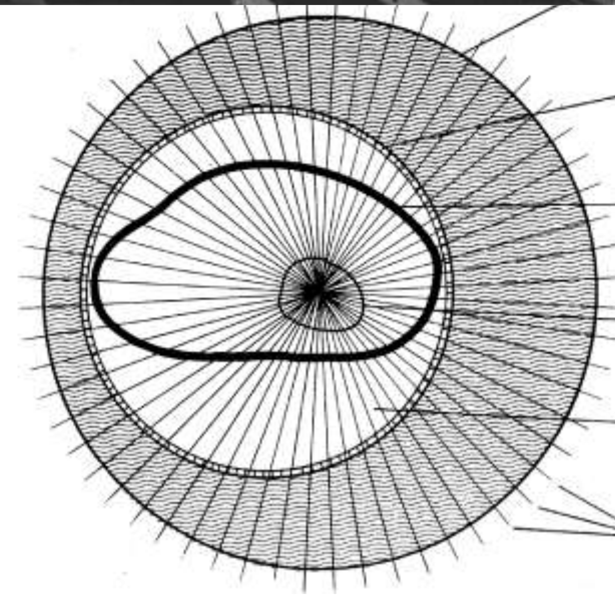

Fokas *et al.* 2009, *Biochimica et Biophysica Acta* **1796** 2

# Piotron (PSI): pion therapy 1980 – 1993



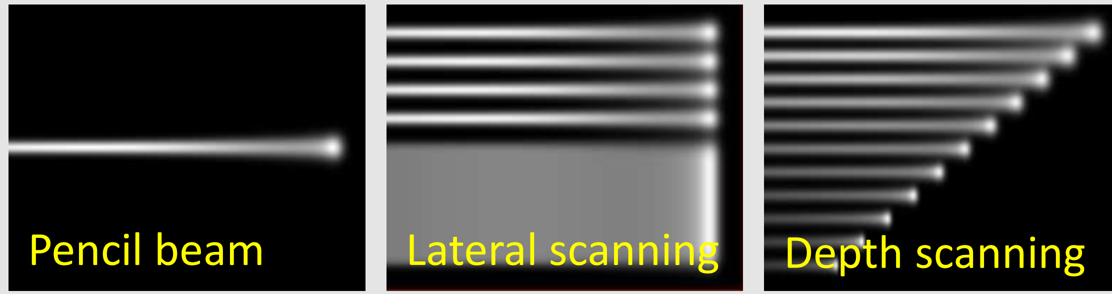



- 590 MeV, 20 µA protons on pion production target
- 60 concentric pion beams focused in one spot
  → Pion '*spot scanning*', patient was moved in *x*, *y*, *z*
  → Development of 3d-inverse planning
- Most advanced facility, 2 installations at other places
- Moderate clinical success:
  – Large spot size (5x larger than protons)
  – No benefit from high-LET



# From passive scattering to active pencil beam scanning

- Charged particles can be directed by electro-magnetic fields
- Experimental set-up to demonstrate technical feasibility of scanning with protons (1990)
- Horizontal beam line:
  – Beam scanning in only one direction
  – Rang shifter for energy modulation
- Similar developments also at GSI



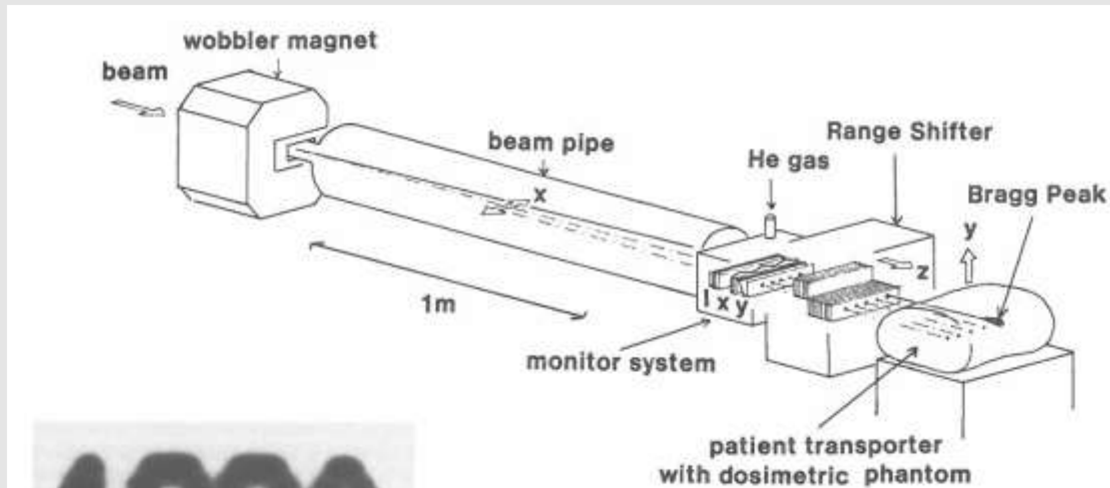





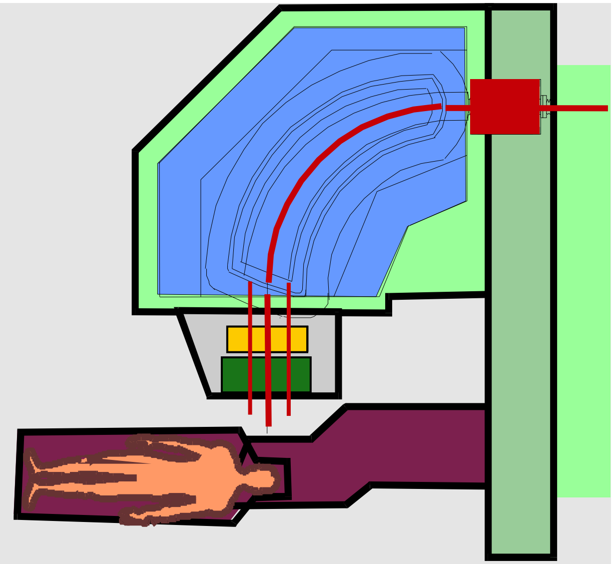
Fig. 4: X ray film irradiated with the 200 MeV proton beam using the spot scanning method.

# Dynamic pencil beam scanning on Gantry 1

- PSI Gantry 1 (1996): Implementation pencil beam scanning

- Very compact (r = 2m) design due to eccentric rotation

- Step-and-shoot scanning

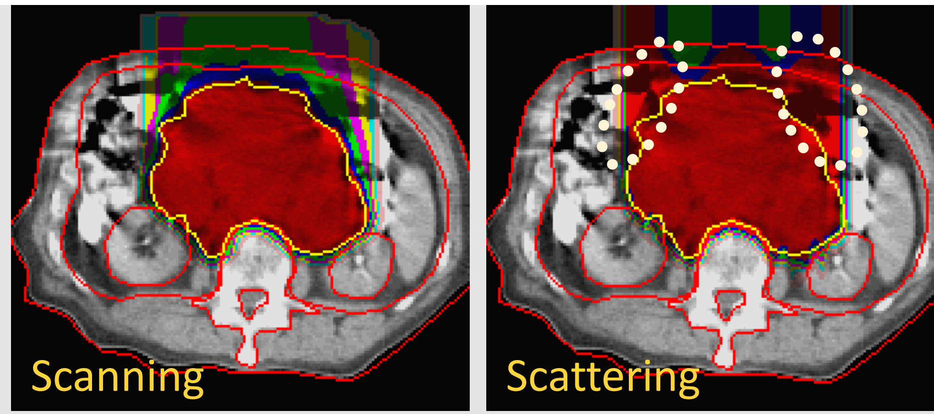


- Elements of scanning:

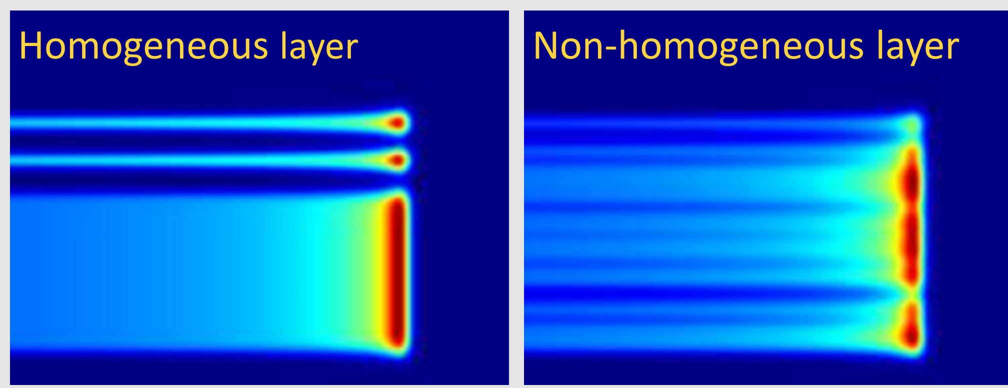
| | | | |
|---|---|---|---|
| Dose | Monitor + Kicker magnet<br>100 μs reaction time | | |
| x | Sweeper magnet | 6 ms/step | ***fast*** |
| y | Range shifter | 100 ms | ***average*** |
| z | Patient table | 1 cm/s | ***slow*** |

# Main benefit of pencil beam scanning

- Scattering with compensator has a fixed range (SOBP) per field
  - Scanning avoids unnecessary 100% dose to the healthy tissues
  - Especially relevant for large and irregular targets

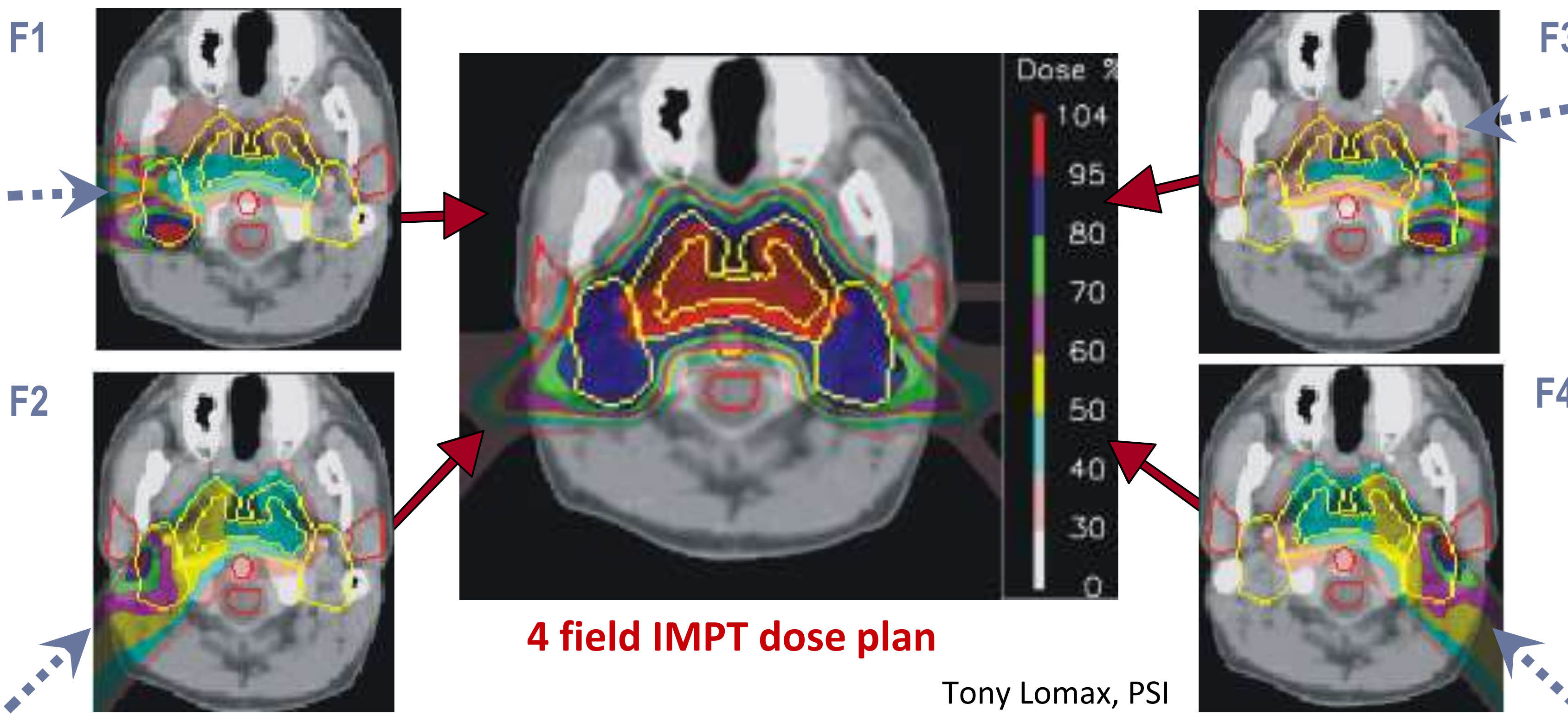



- No patient specific hardware needed (collimator / compensator)
- Scanning can easily deliver non-homogenous energy layers:
  - Optimize dose distribution
  - Biological targeting: Different dose level within the target
  - Improved planning flexibility with *Intensity Modulated Proton Therapy* IMPT



# Better dose distributions with Intensity Modulated Proton Therapy (IMPT)

- Each **single dose field** delivers non-uniform dose field
- Uniform dose in target by superposing all field
- Better dose conformation for complex target geometries
- IMPT is only possible with spot scanning technique!




**4 field IMPT dose plan**

Tony Lomax, PSI

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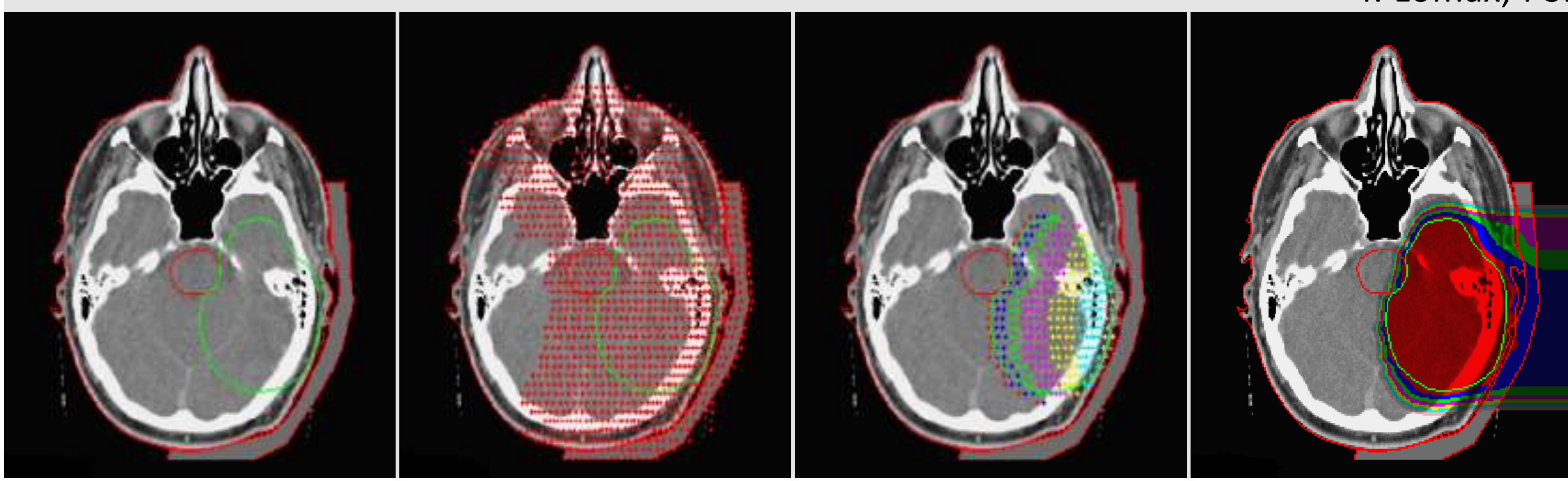
# Pencil beam scanning requires high computer power

- Spot grid distance ≤ 5 mm
  Target with 1 l: ≈10’000 Bragg-Peaks
- Optimization algorithm: $\chi^2$
- Constraints on dose to target and critical organs
- No unique solution, many solutions with same dose distribution (Degeneracy)

- The availability of sufficient computing power was a necessary prerequisite for the development of PBS
- Still today, there are limitations:
  - Definition of field direction: by hand
  - ‘Simple’ analytical beam models (1 or 2 Gaussian profile)
  - No real-time optimization

T. Lomax, PSI



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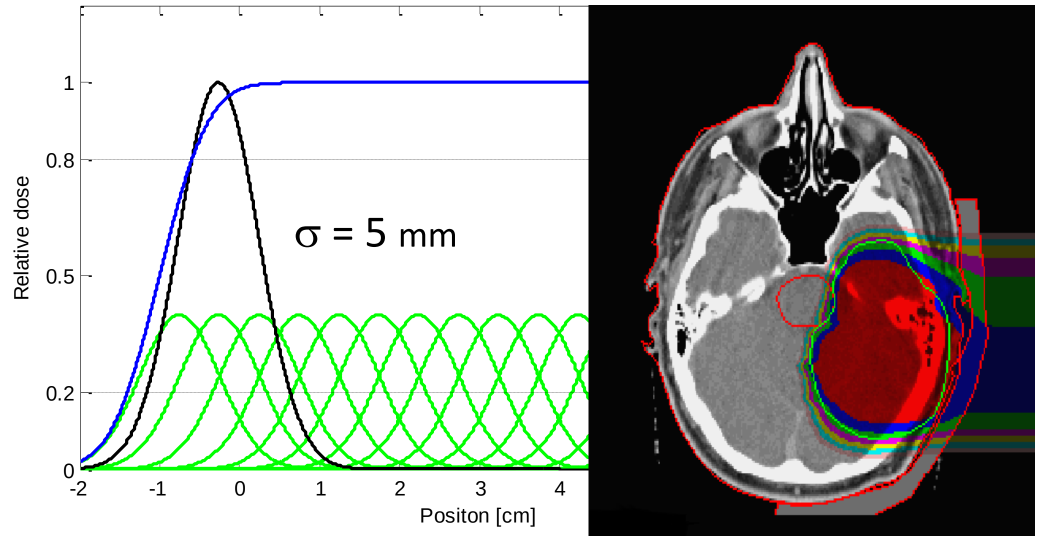
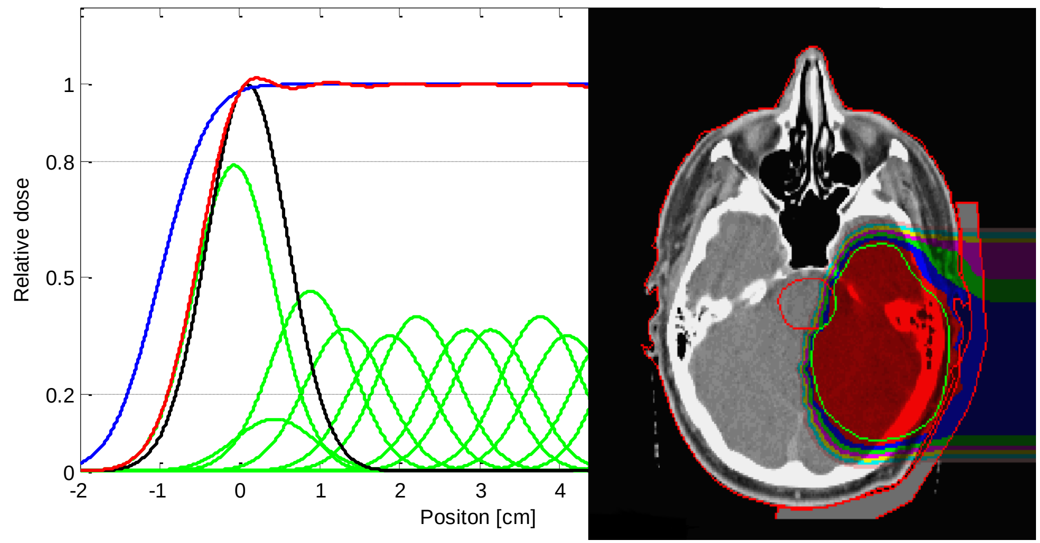
# “Edge enhancement” capability of PBS

- Uniform fluence of spots: Error-function
- Penumbra (80% - 20%):
  - Error function: 1.7σ
  - Gauss: 1.1σ → 1.5x penumbra
- PBS delivery: Flexibility in
  - Beam intensity
  - Spot position
- The dose lateral fall-off can approach the fall-off of the original Gaussian spot
- Only optimization unfolds the full potential of PBS.



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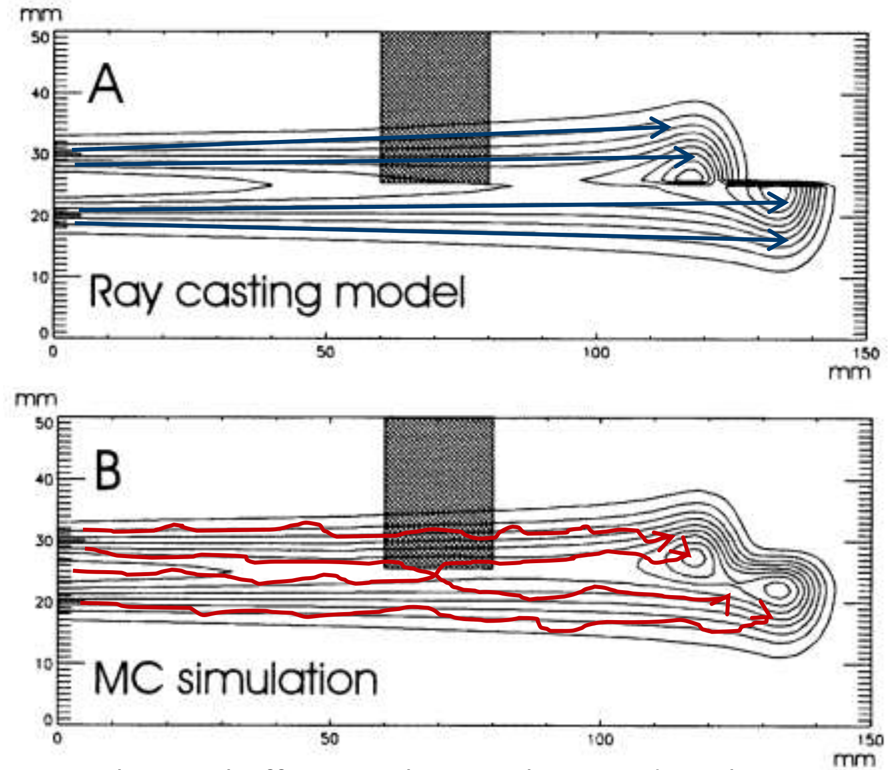
# Increasing dose calculation accuracy with MC simulation

**Current pencil beam algorithms:**

- Analytical model
- Fast computational
- Compromised accuracy in presence of inhomogeneity

**Dose calculation by MC**

- Range dilution due to multiple Coulomb scattering
  A Tourovsky *et al* 2005 *Phys. Med. Biol.* **50** 971
- Include relative biological effectiveness (RBE)
- Long computation time (hours)



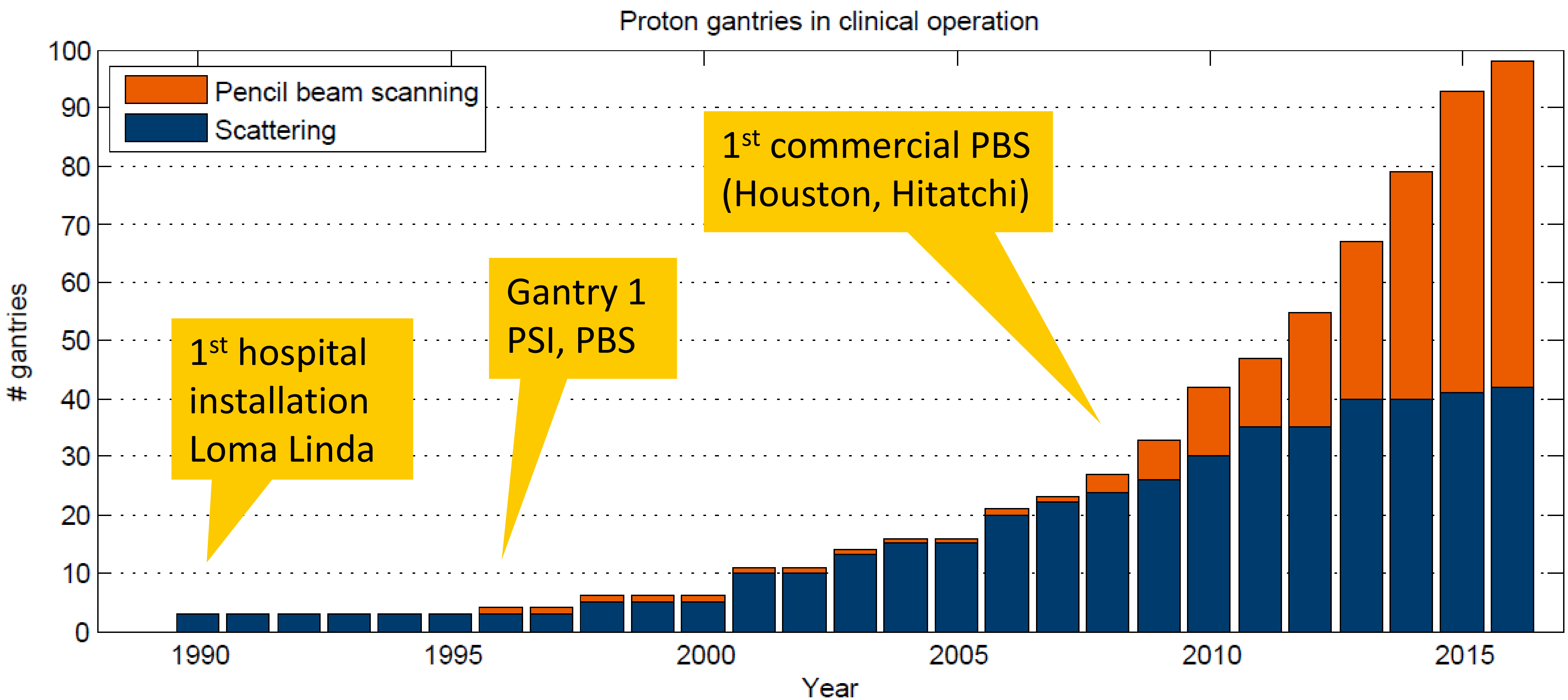

Barbara Schaffner *et al* 1999 *Phys. Med. Biol.* **44** 27

➢ Developments towards GPU-based Monte Carlo treatment planning optimization
  Yongbao Li *et al* 2017 *Phys. Med. Biol.* **62** 289

# PBS was clinically accepted during last 10 years

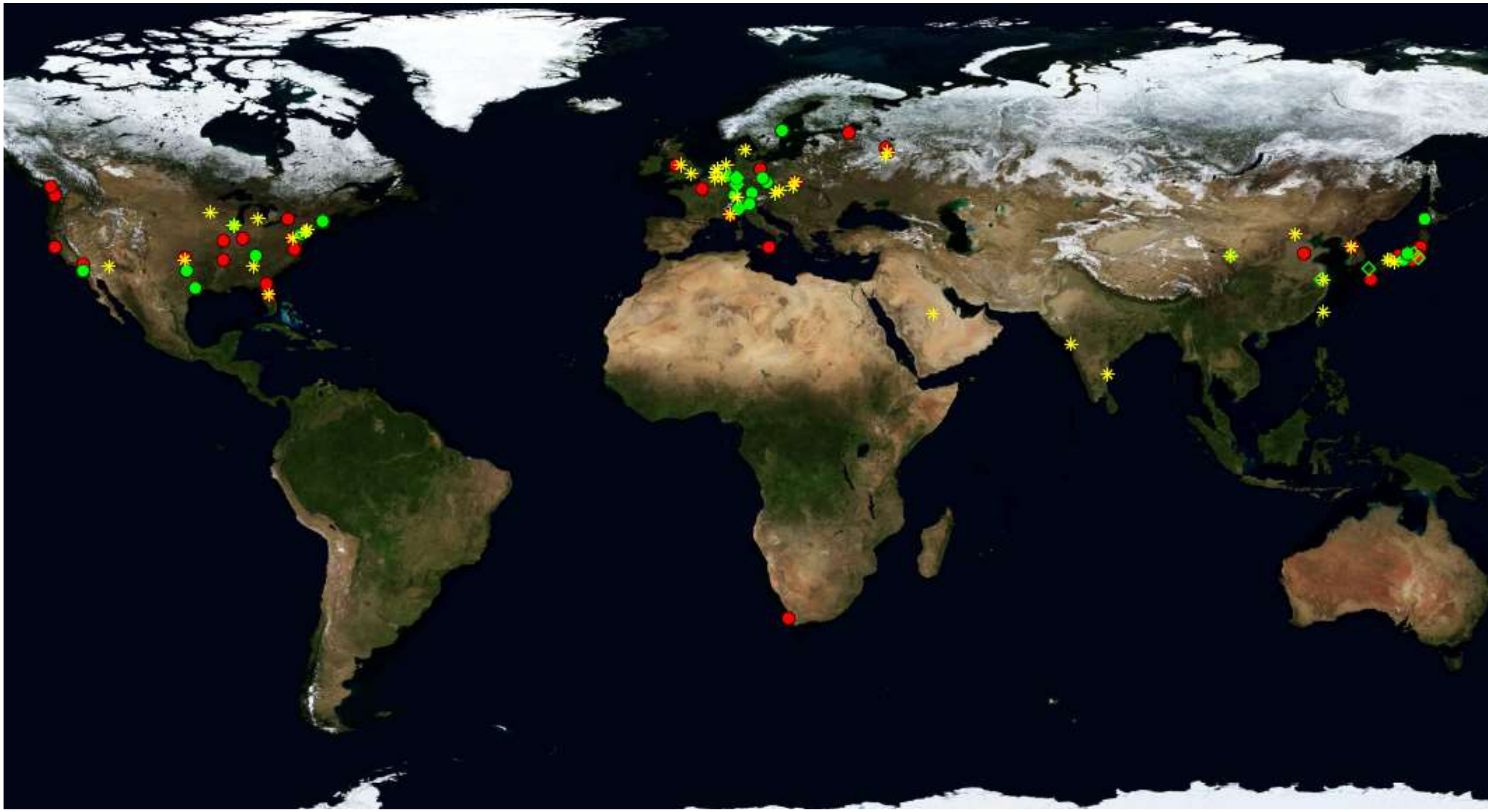
Number of proton gantries in clinical operation separated by delivery technique

- About 10 new gantries per year
- All new systems are PBS only




based on: Meer et al., Mod. Phys. Lett. A 30 (2015)

# ~70 particle therapy centres in operation



Scattering  Scanning  Heavy ions  Future centres

end of 2016, based on data from https://www.ptcog.ch/

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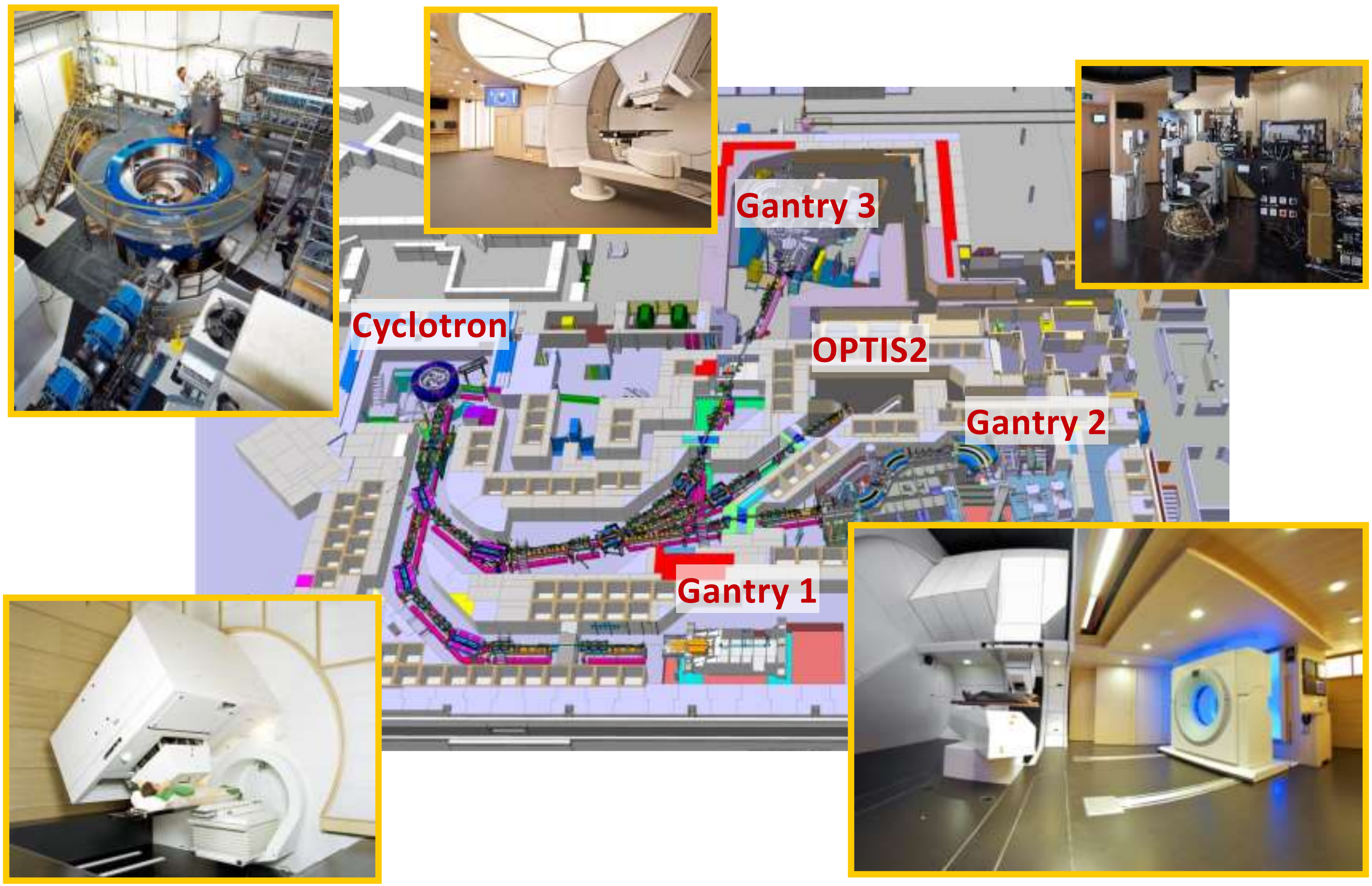
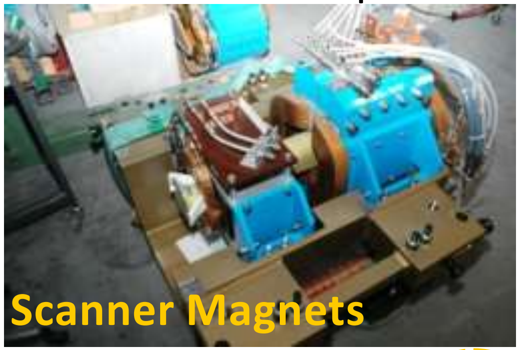
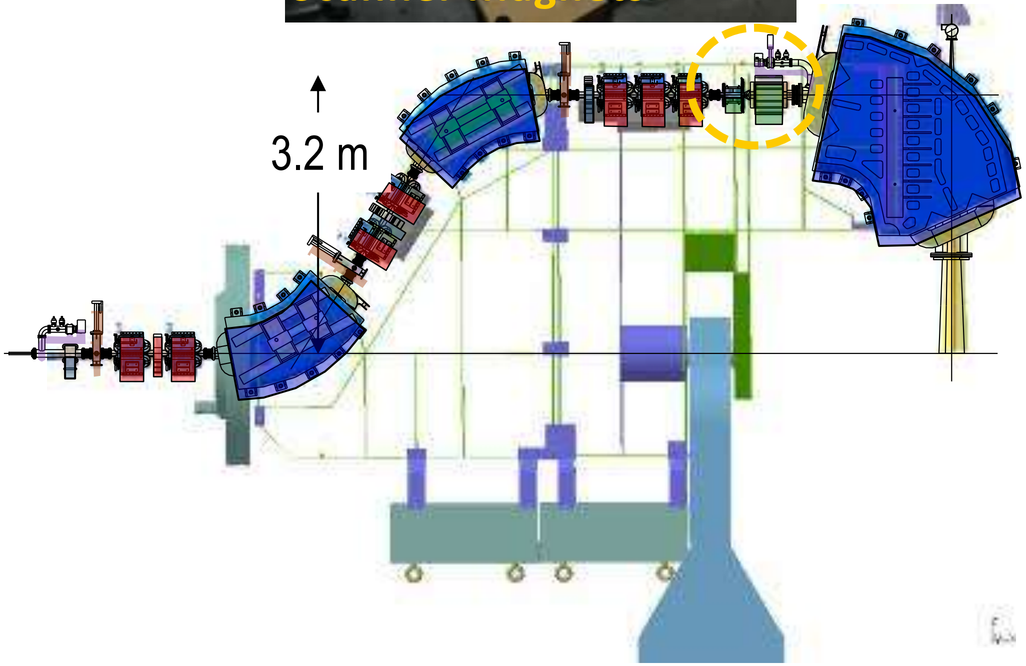
# PSI Gantry 2 at PROScan: Clinical operation and R&D platform



# Gantry 2 at PSI: Fast beam scanning

- Orthogonal set of sweeper magnets
  - Beam deflection up to 2 cm/ms

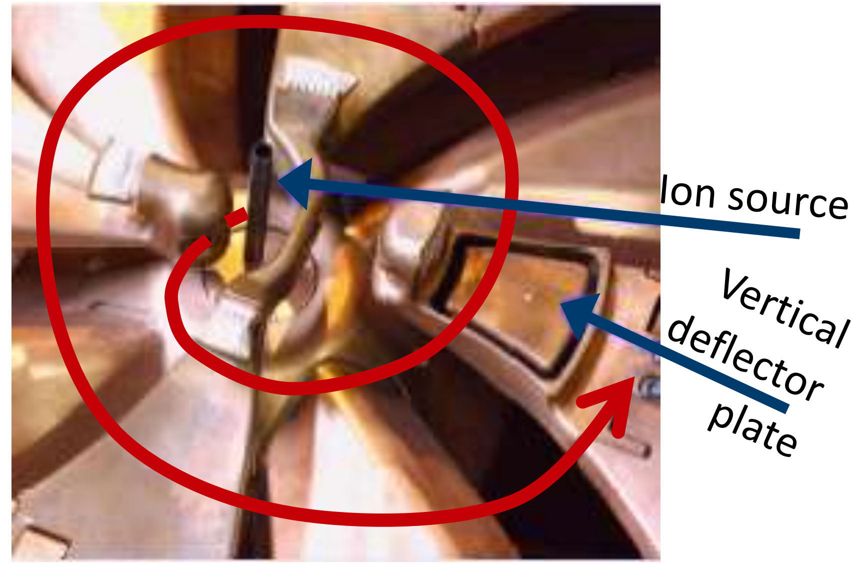


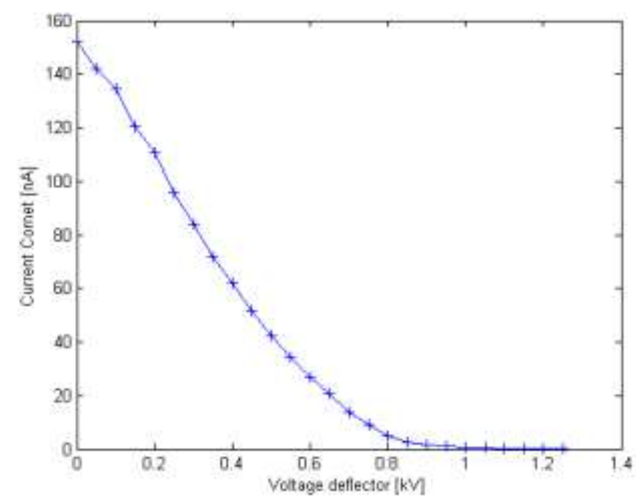




- «Up-stream» scanning
  - Parallel beam
  - Smaller gantry radius
  - … but larger (heavier) dipole
- Achromatic beam optic
- Nozzle with
  - Dose / position monitor
- Start clinical operation 2013

# Cyclotron COMET: Fast intensity modulation

- Superconducting coil (liquid helium)
- 250 MeV / up to 1 µA beam
- Operating since 2007
- Fast beam intensity modulation with vertical deflector
  - Electrostatic beam deflection inside accelerator (~50µs)
  - ~1 kV to suppress beam



# Dynamic beam current control in discrete spot scanning: Close interaction with accelerator

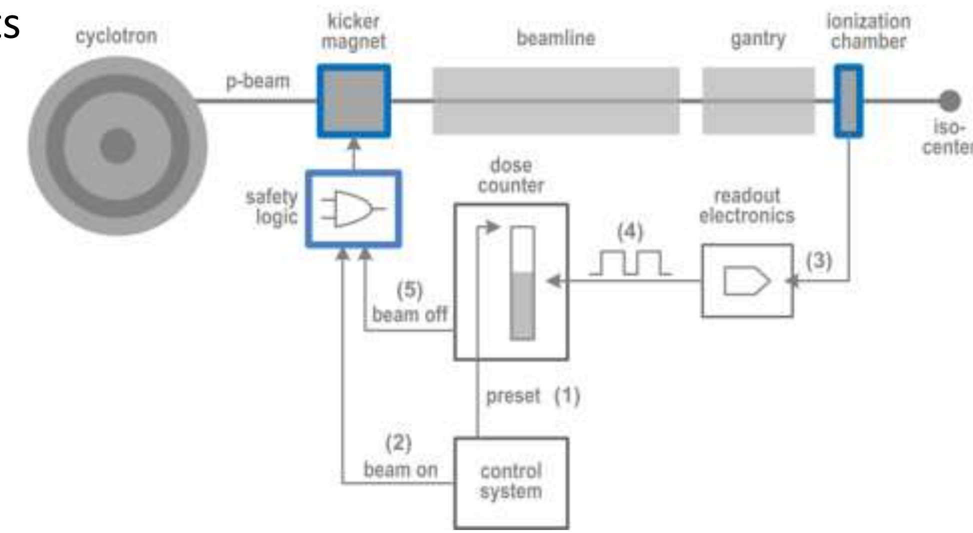
- Latency of beam switch-of results in extra dose (proportional to beam current)

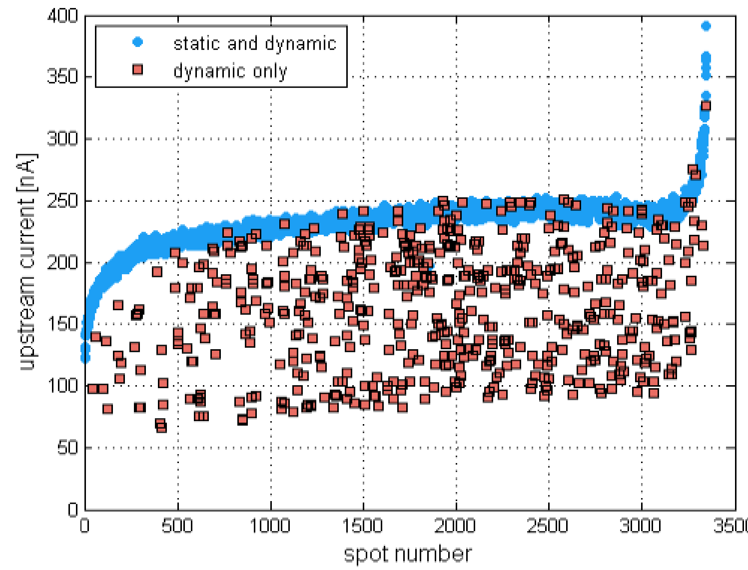
- Subtraction of predicted extra dose on each planned dose

- No correction possible if latency longer than delivery time

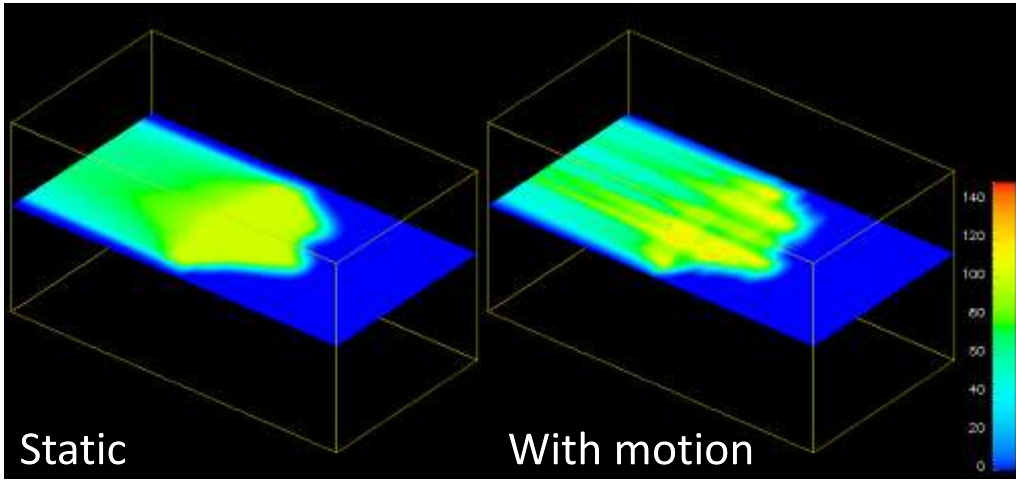
➢ Adapt beam current (lower) for each dose spot
  - Improved dose distributions
  - Insignificant longer treatment time

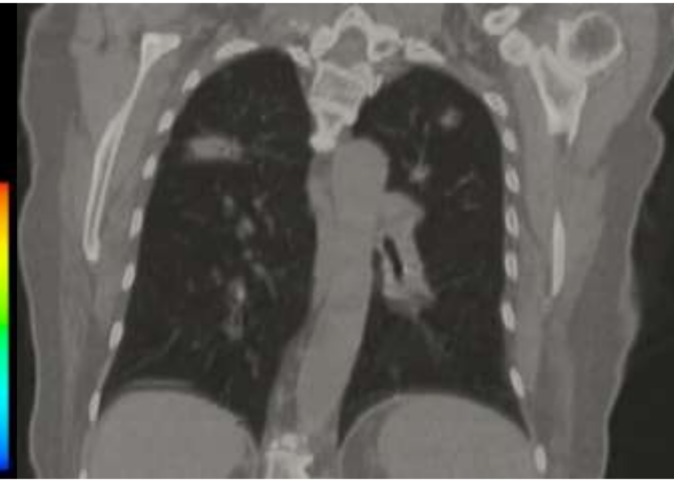
- In clinical operation since 2017 (C. Bula)



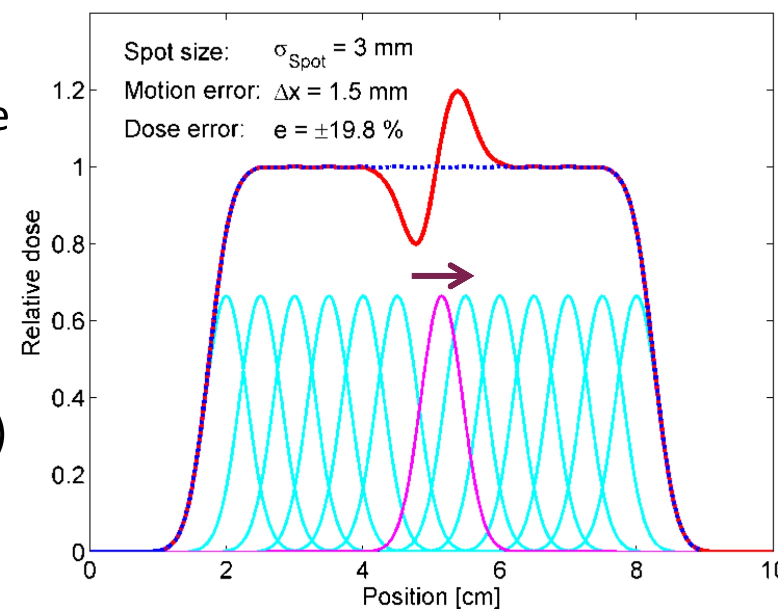
# A mayor challenge in PBS: Moving targets / organ motion



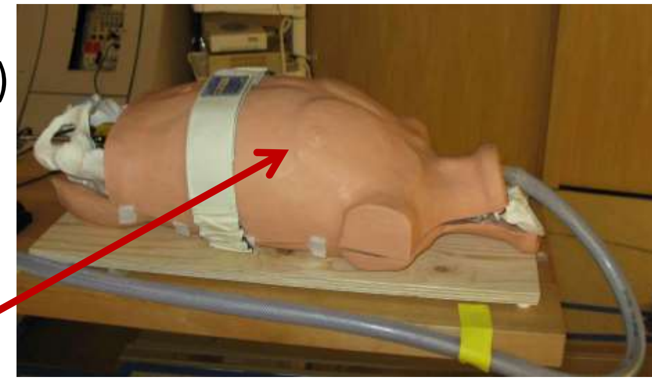
- Interplay effect between beam delivery sequence and organ motions destroys dose homogeneity
- Mitigation techniques:
  - Deliver dose multiple times (Rescanning)
  - Patient hold his/her breath (Breath-hold)
  - Irradiation only in exhaled phase (Gating)

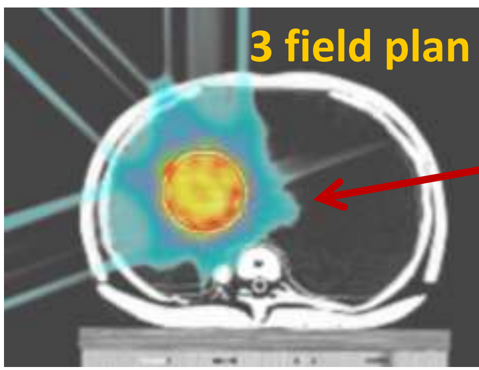
⇨ All approaches require fast beam delivery



# Experimental validation of rescanning

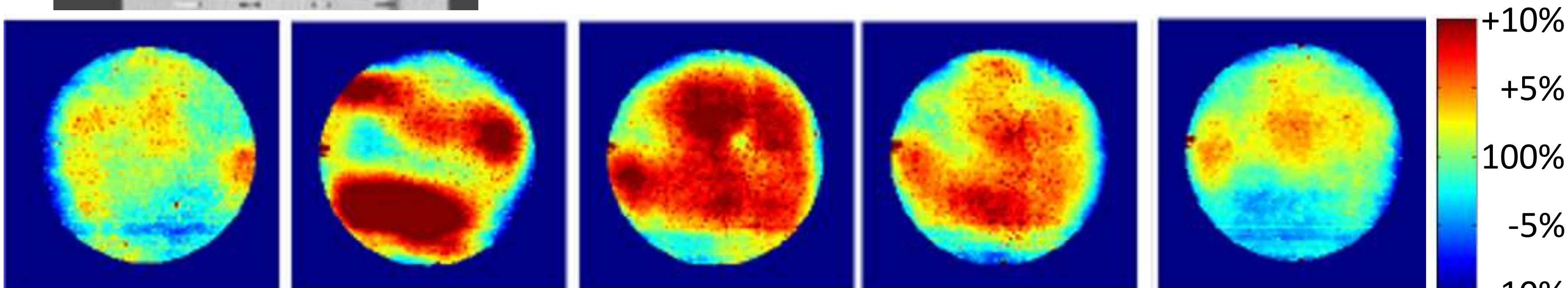
- Anthropomorphic phantom with lung tumour and tissue equivalent materials (bone, skin, lung)
- Simulation of different breathing parameters
- Rescanning to minimize motion interferences
  → Dose homogeneity can be recovered






Tumour with insert for dose measurements with film

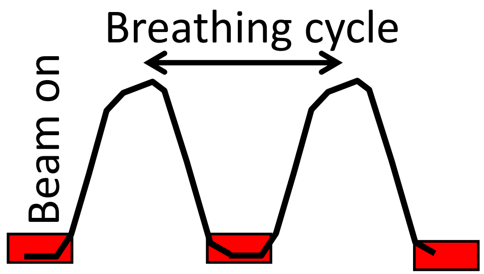
R. Perrin, PSI



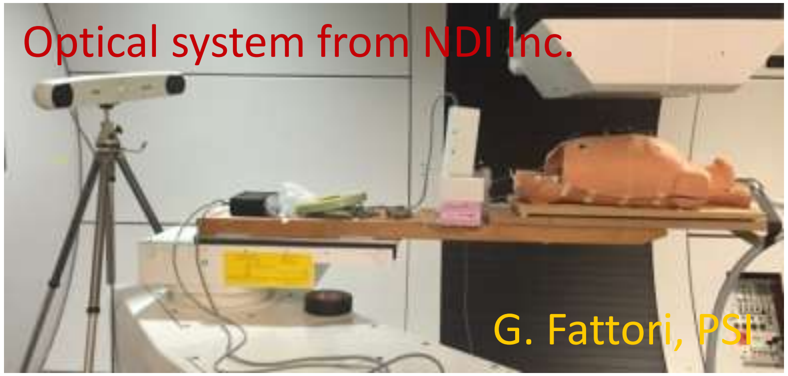

Static | Motion, 1 cm | 2x rescanning | 5x rescanning | 8x rescanning

# Gating and Breath-hold

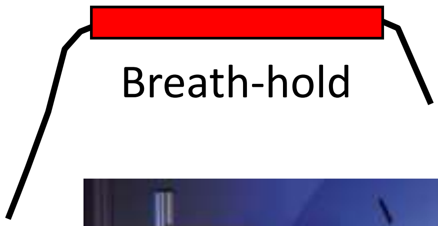
**Beam gating**




- Breathing is externally monitored
- Irradiation only during defined window (e.g. exhale phase)
- Longer treatments
- Interaction with dose delivery




**Breath-hold**




- Patient actively hold his breath
- Irradiation only during breath-hold window

Benefit:

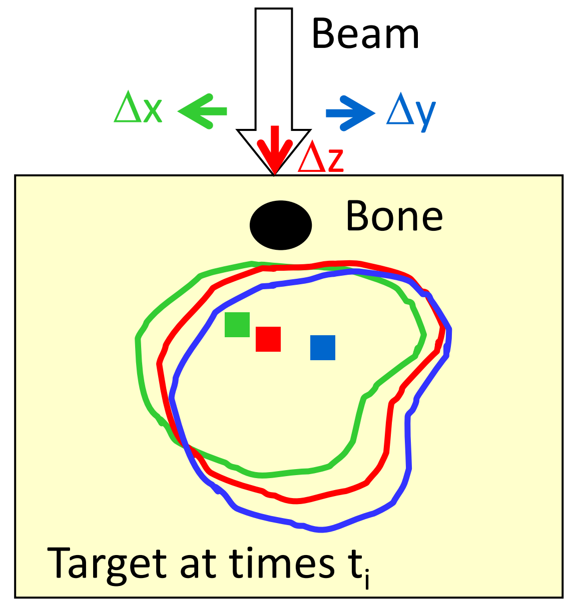
- Dose application in quasi-static condition
- Efficient irradiations

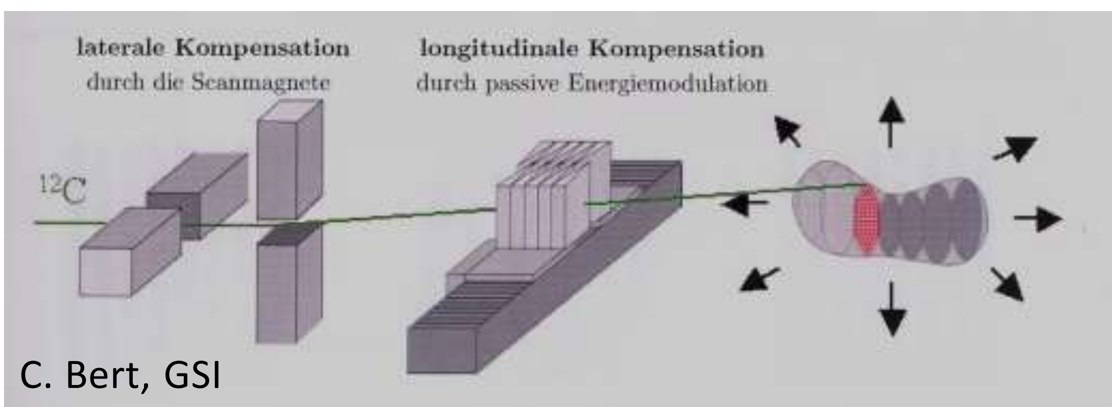
- Attractive if dose can be delivered to target in < 10s

→ Fast dose delivery is essential for both techniques ←

# Motion mitigation with target tracking?

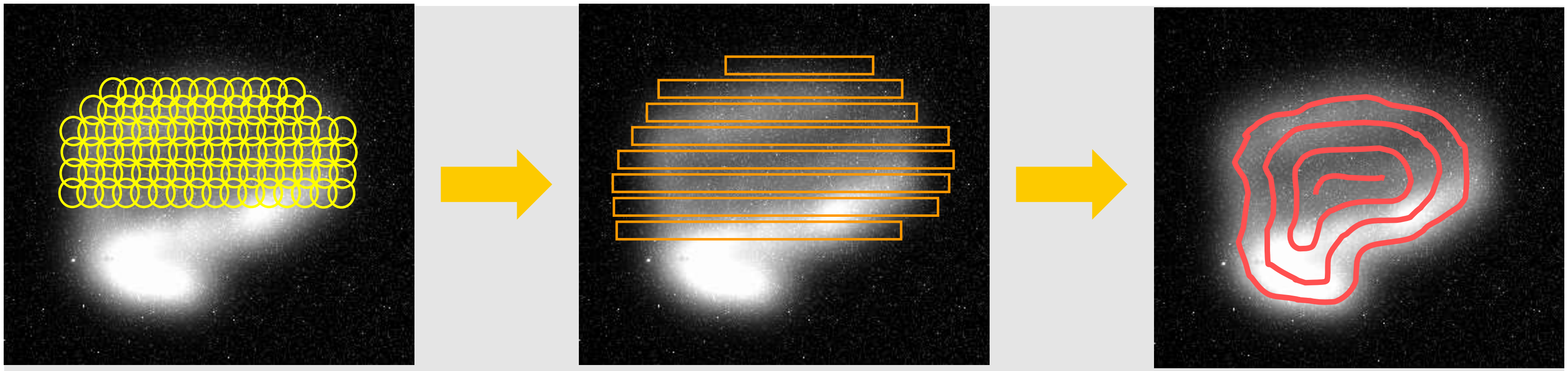
- Active corrections in the beam delivery to follow the track of the tumor:
  - Lateral corrections ($\Delta x$, $\Delta y$)
  - But also energy corrections ($\Delta z$) due to tissue inhomogeneities
- Many (unsolved) issues:
  - How to detect motion? (Correlation between internal tumor movement and external surrogate)
  - Tumor deformation? → Online dose adaptation
  - Density changes proximal to tumor (Rib bones before lung tumor)
- A lot of expertise developed at GSI



C. Bert, GSI

# Advanced scanning modes



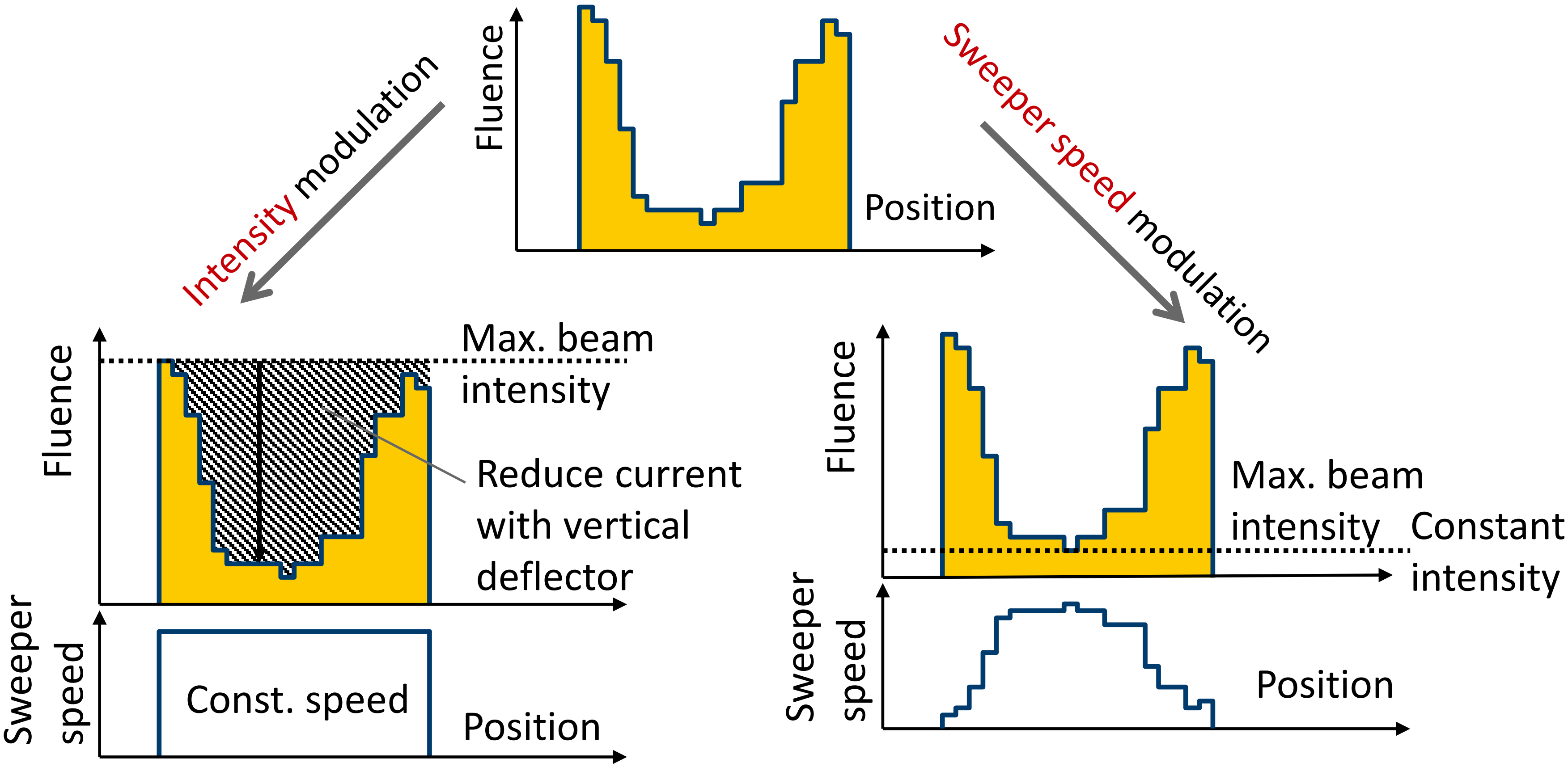
**Discrete spot scanning (Gantry 1)**
- Switching off the beam after each spot
- Dead time per spot ~3 ms.
  - 10'000 spots → 30 s dead time, scales with number of rescans!

**Raster – Scanning**
- Beam-on from spot to spot position
- Transient dose: Limiting factor
- Today commercial default

**Continuous line scanning**
- Paint lines with intensity modulation
- Minimize dead time
- Optimize rescanning capability

**Contours scanning (?)**
- For optimizing repainting *and* lateral fall-off (difference Gaussian to error-function)

# Line scanning: Intensity vs. speed modulation




- Suppress beam with vertical deflector
- Wasting protons, hence less efficient

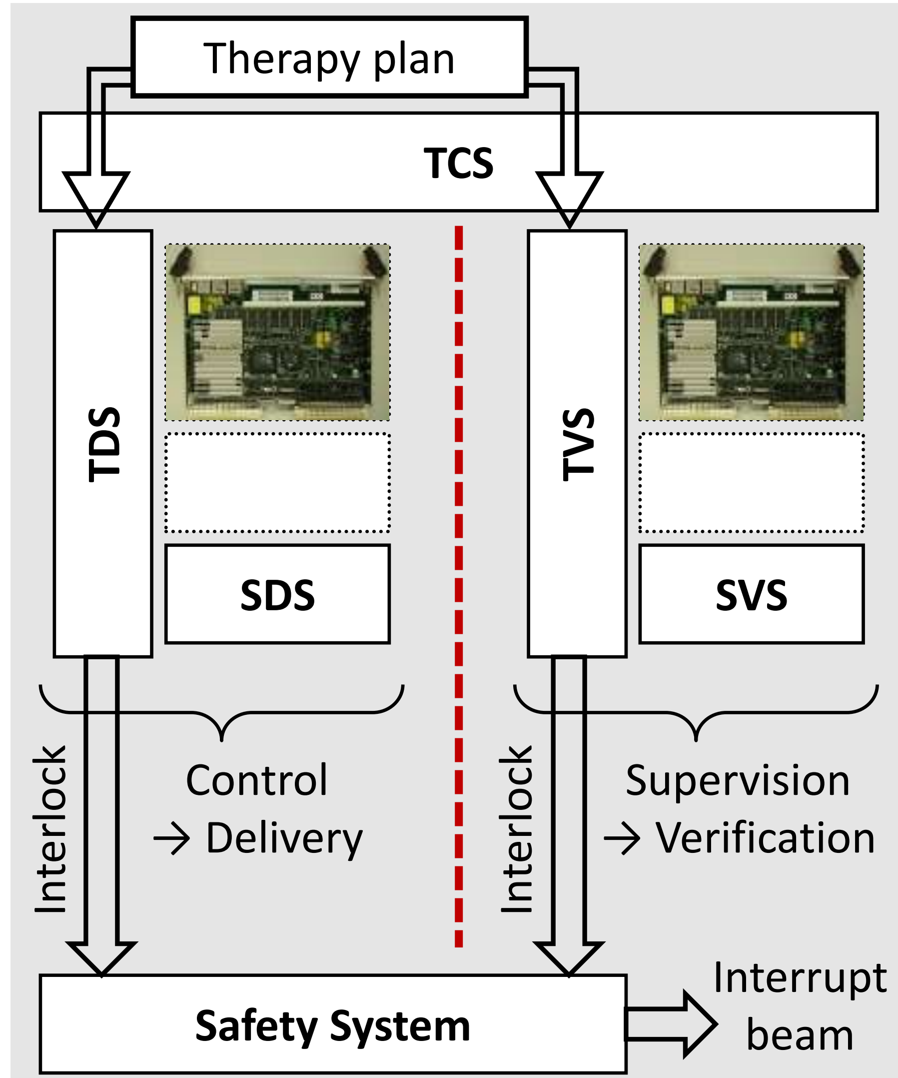
- Modulate sweeper scan speed
- Work with maximal proton current
- Problem: Painting low dose profiles

⇨ Use primarily speed modulation and where necessary intensity modulation

# Therapy control system architecture

Therapy Control System (TCS):
- Therapy Delivery System (TDS)
- Therapy Verification System (TVS)

- VME system with MVME6100
- Therapy plan with spot sequence is delivered to both systems
- Independent control of and verification of actuators (redundancy and diversity)
- TVS or TDS can raise interlock



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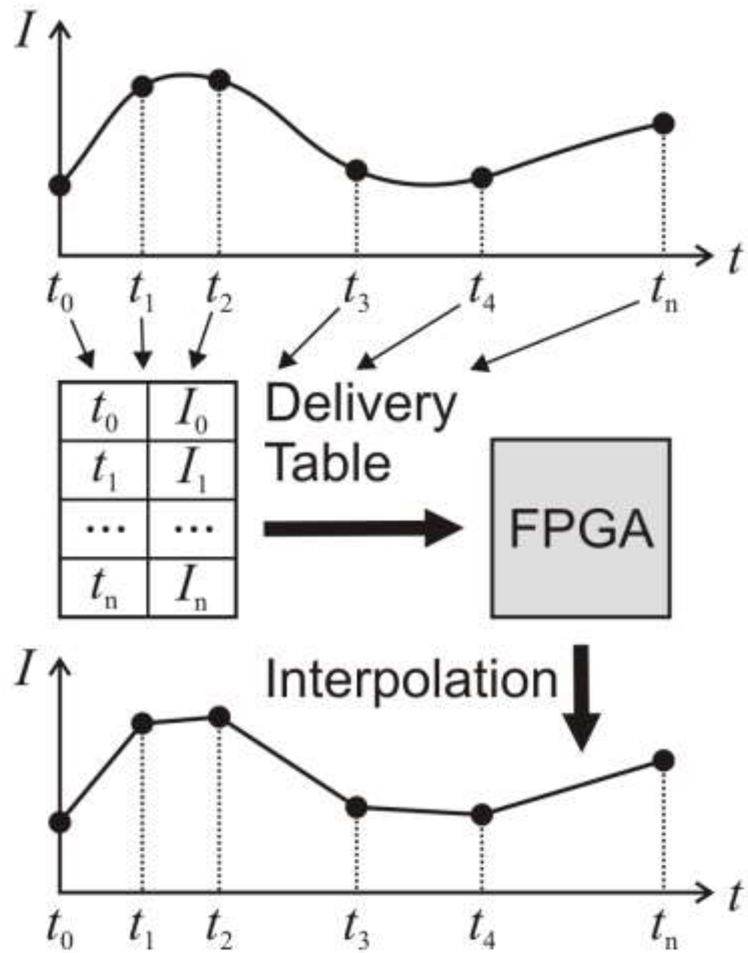
# Scanning Delivery System (SDS) for continuous scanning

- Synchronous control of fast actuators:
  - Magnet current (Sweeper magnets, *x*/*y*)
  - High-voltage (Deflector plate, *I*)

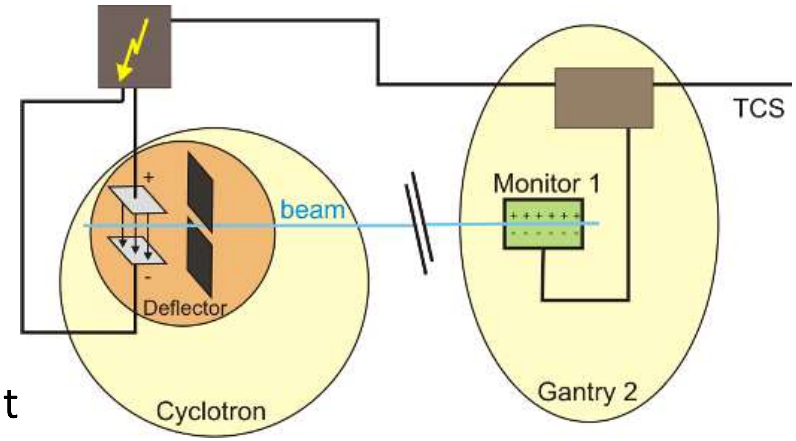
- Delivery table with pre-calculated values are downloaded into an FPGA
- FPGA interpolates data in real time and send set-point to actuator with 100 kHz

- Realised on FPGA-PMC card of TDS

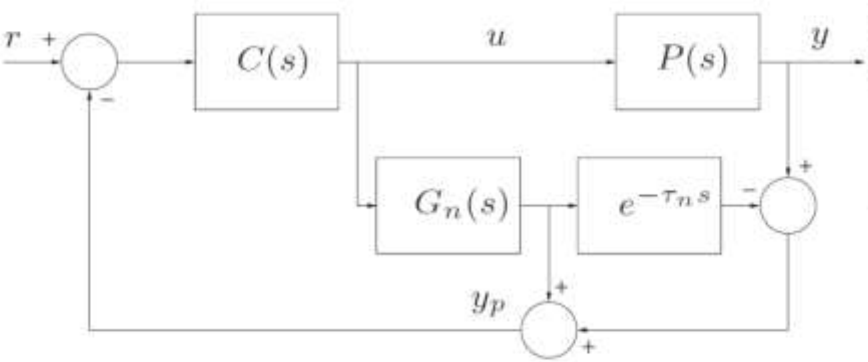



# Accurate beam current regulation with improved controller design

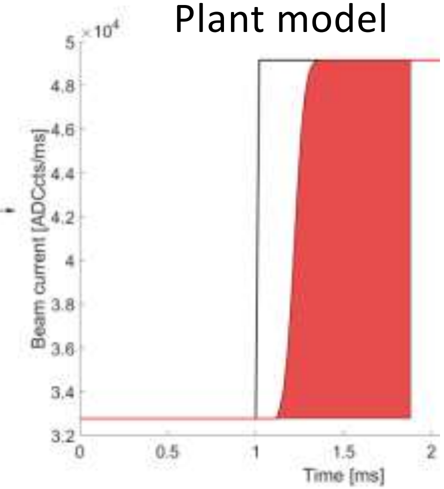
- Feedback loop based on dose monitor in front of patient controls beam current
- Large system delay (~150 us):
  - Particle acceleration / transport
  - Dose measurement (charge collection)
- Advanced controller with smith predictor
  - „Dead-time compensator“, predicts plant output ***P(s)*** using a plant model ***G(s)***
  - Controller ***C(s)*** designed without delay
- Implemented on FPGA of SDS
  - Runs at 100 kHz



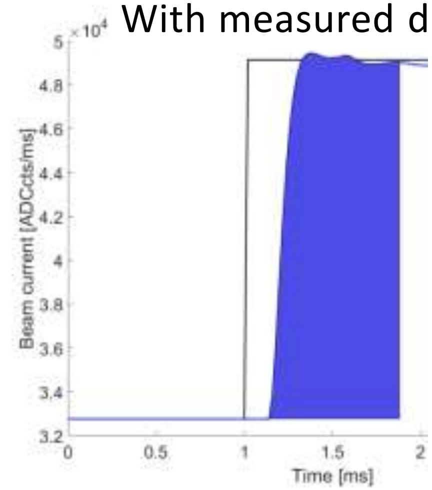

P. Fernandez, PSI



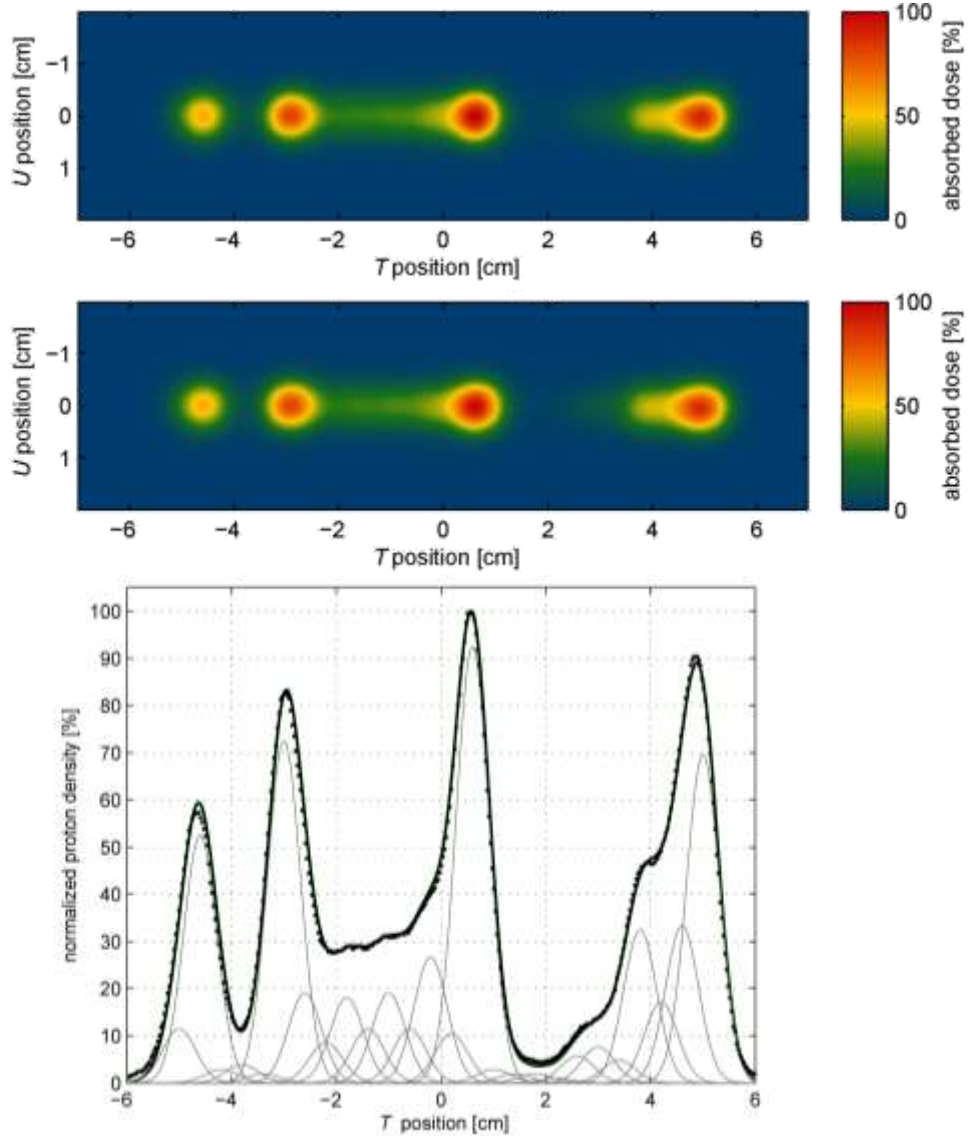

Plant model




With measured data



# Comparison on scintillating screen: Spot scanning vs. Continuous scanning




**Discrete spot scanning**

Spot weights:

$10^6$ to $10^8$ protons / spot

**Line scanning**

Scan speeds:

0.01 to 1.00 cm/ms

**Measured dose profile**

with strip chamber

in nozzle

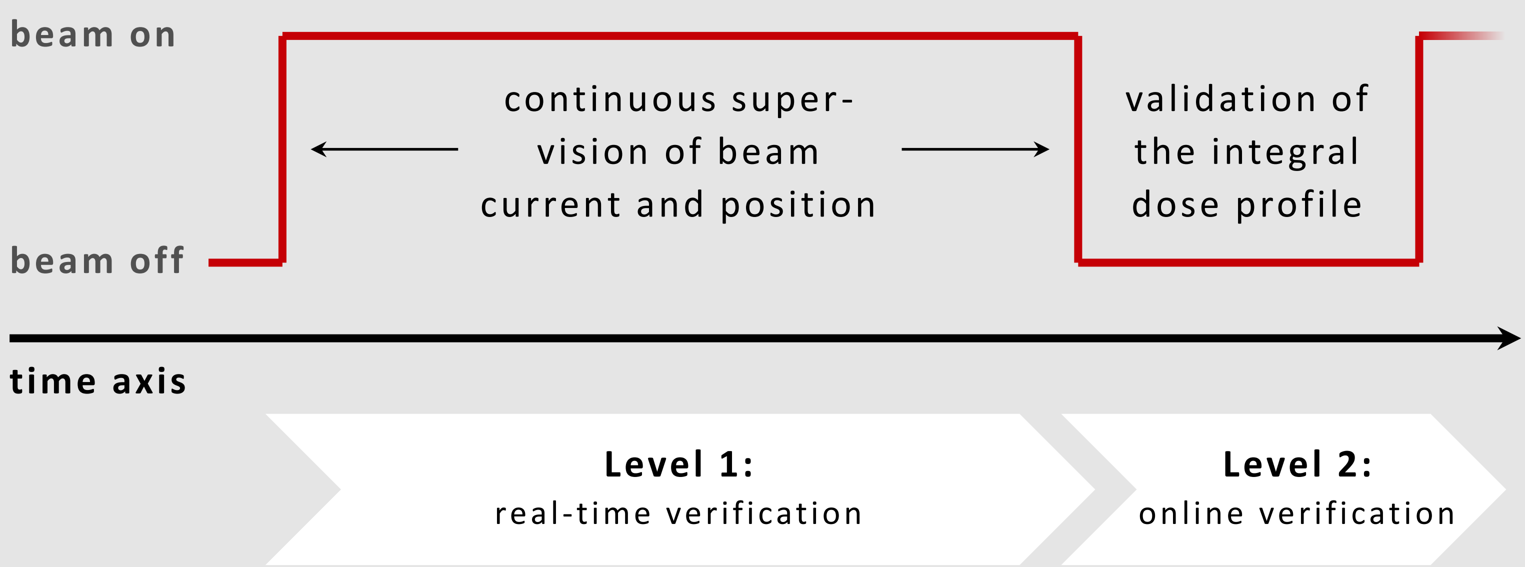
•••• spot scanning

——— line scanning

# Scanning Verification System SVS for continuous scanning: Concept

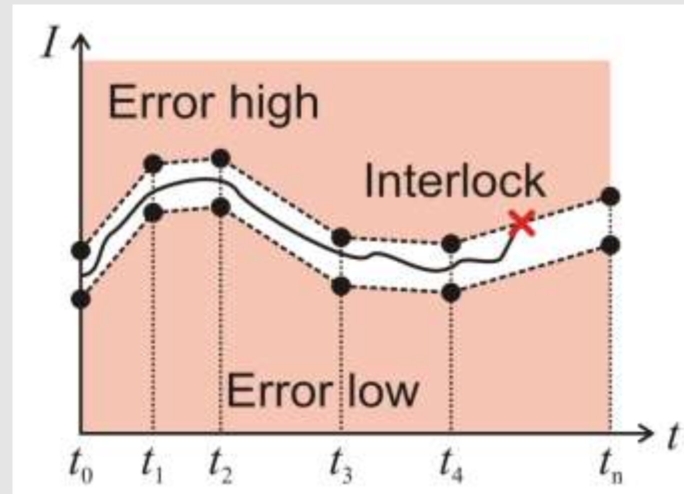
- Level 1:
  Real-time monitoring during the application of a line to prevent radiation incidents

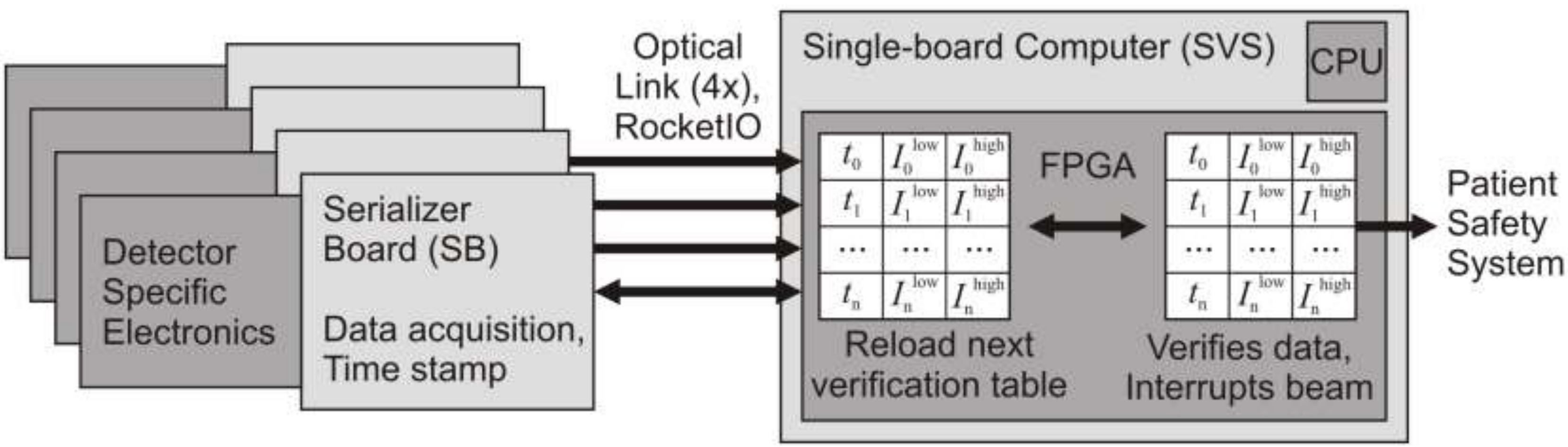
- Level 2:
  Online verification after the application of a line to assess and validate delivery accuracy



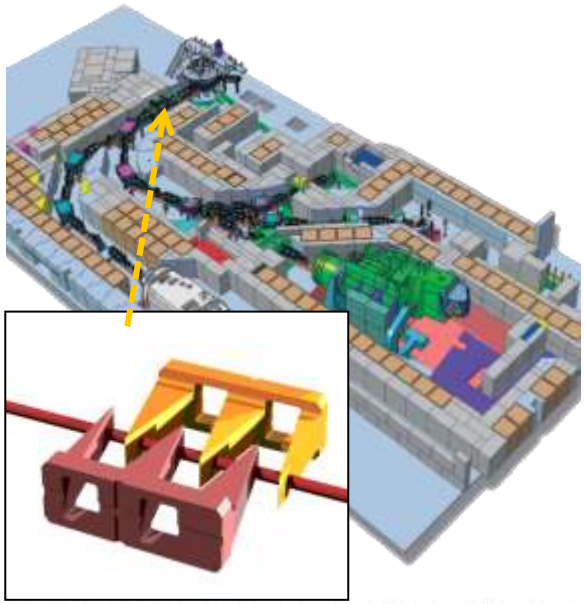
# Scanning Verification System SVS for continuous scanning : HW implementation

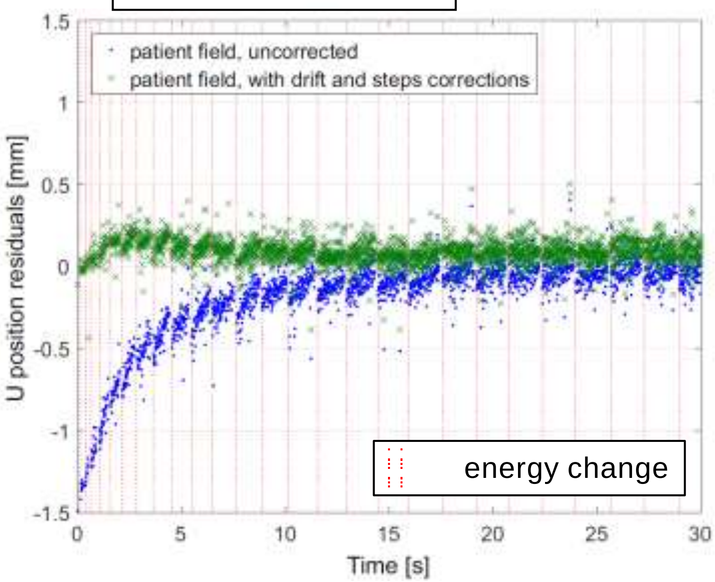
- Sensor data is sampled with detector specific electronics DSE
- Serializer board (SB) transmit data over optical link (2.5 GBit/s) to FPGA every 10μs
- Verification table error band on FPGA
- Interpolation of error band and validation of data in real-time on FPGA (analogue TDS)
- Beam interruption in case of error



# Fast changes of the beam energy

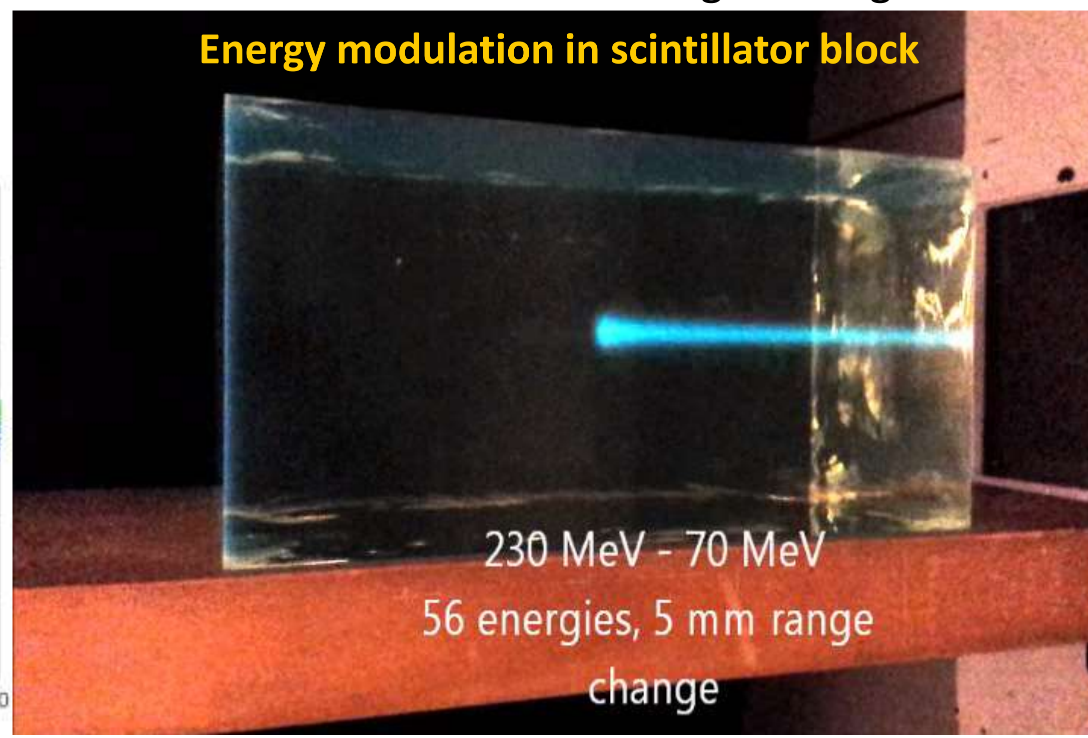





PROScan was optimized for fast energy changes:

- Fast mechanical degrader
- Laminated magnets / dedicated power supplies
- On-line corrections of 'drift' effects
- Realized on Gantry 2:

  <100ms dead time for 5mm change in range



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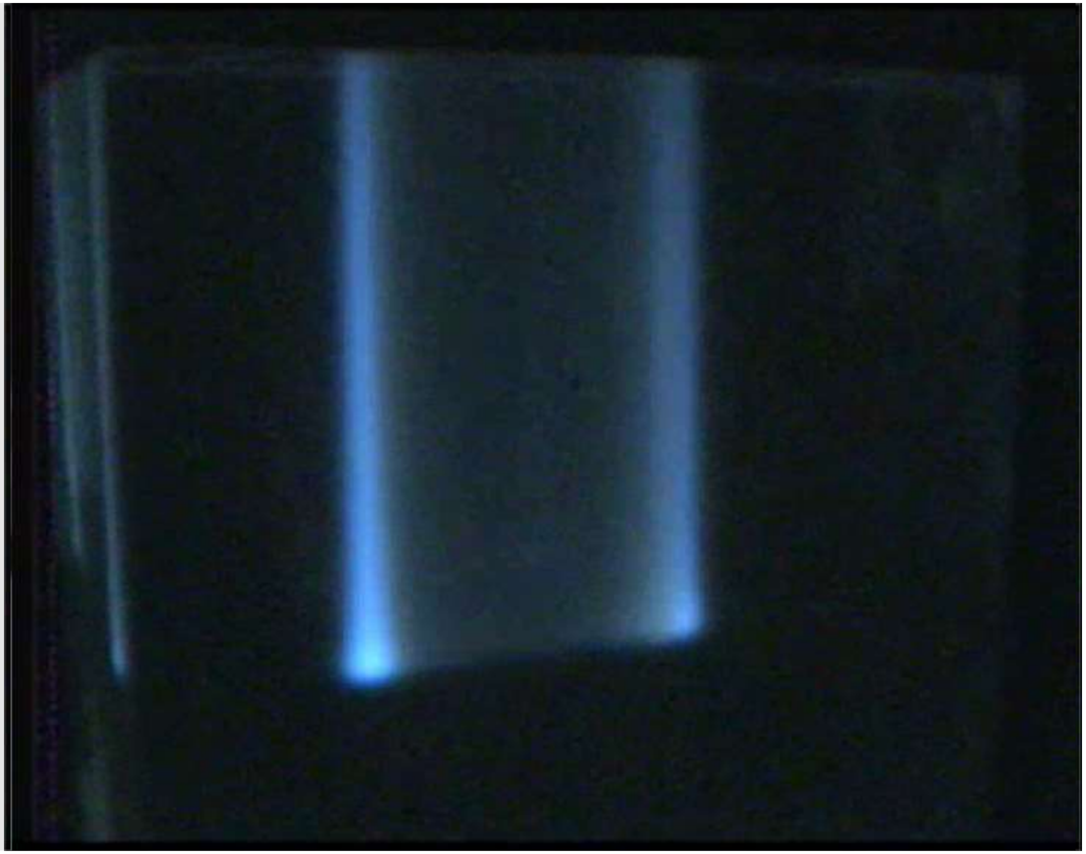
# Demonstration of fast conformal line scanning

- Delivery of 3 dose distributions with line scanning: Box / Diamond / Sphere
- Dose: 0.2Gy / Delivery time ~10s
- Combination of sweeper speed and beam intensity modulation

Experimental setup:

# Summary and conclusion

- Charged particle have an inherent advantage in radiation therapy (Bragg-Peak)

- Technology promoted the development of Pencil Beam Scanning:
  - Optimized dose distributions with Intensity modulated proton therapy (IMPT)
  - Help to establish proton therapy in radiation therapy

- Effective treatment of moving targets require fast and dynamic beam delivery
  - Fast actuators and embedded control loop
  - Real-time supervision of critical parameters (beam current, position)